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Introduction to Ferromagnetism and Patterned Magnetic Nanostructures

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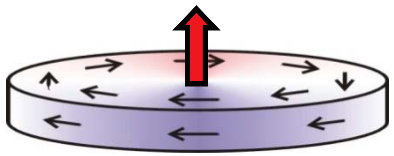


Outline

- **Magnetism and ferromagnetism**
- **Magnetic field, magnetization and M-domains**
- **Nanomagnetism and nanostructures:**

  magnetic stripes, dots, antidots, rings etc.
- **Magnetization distributions: magnetic vortex**
- **Landau-Lifshits equation and contributions to effective field (energy terms)**
- **Conclusions**

What is ferromagnetism?

Classification of materials:

1) Diamagnets will be **repelled from the region of larger magnetic field** (example- noble metals Au,Ag,Cu and organics)
2) Paramagnets are **attracted to the region of larger magnetic field**, like ferromagnets, but the attraction is weak. Paramagnetism is exhibited by materials containing transition elements (3d), rare earths (4f) and actinide elements (5f)
3) Ferromagnets are specific paramagnets which has spontaneous magnetic moment even without external field (Fe, Co, Ni, Gd, Dy…)

Important:

a) **Magnetic moment is not zero at low temeperatures $T<T_c$ (Curie temperature)**
b) **Average moment of macroscopic sample may be zero due to domains**

Magnet - isms

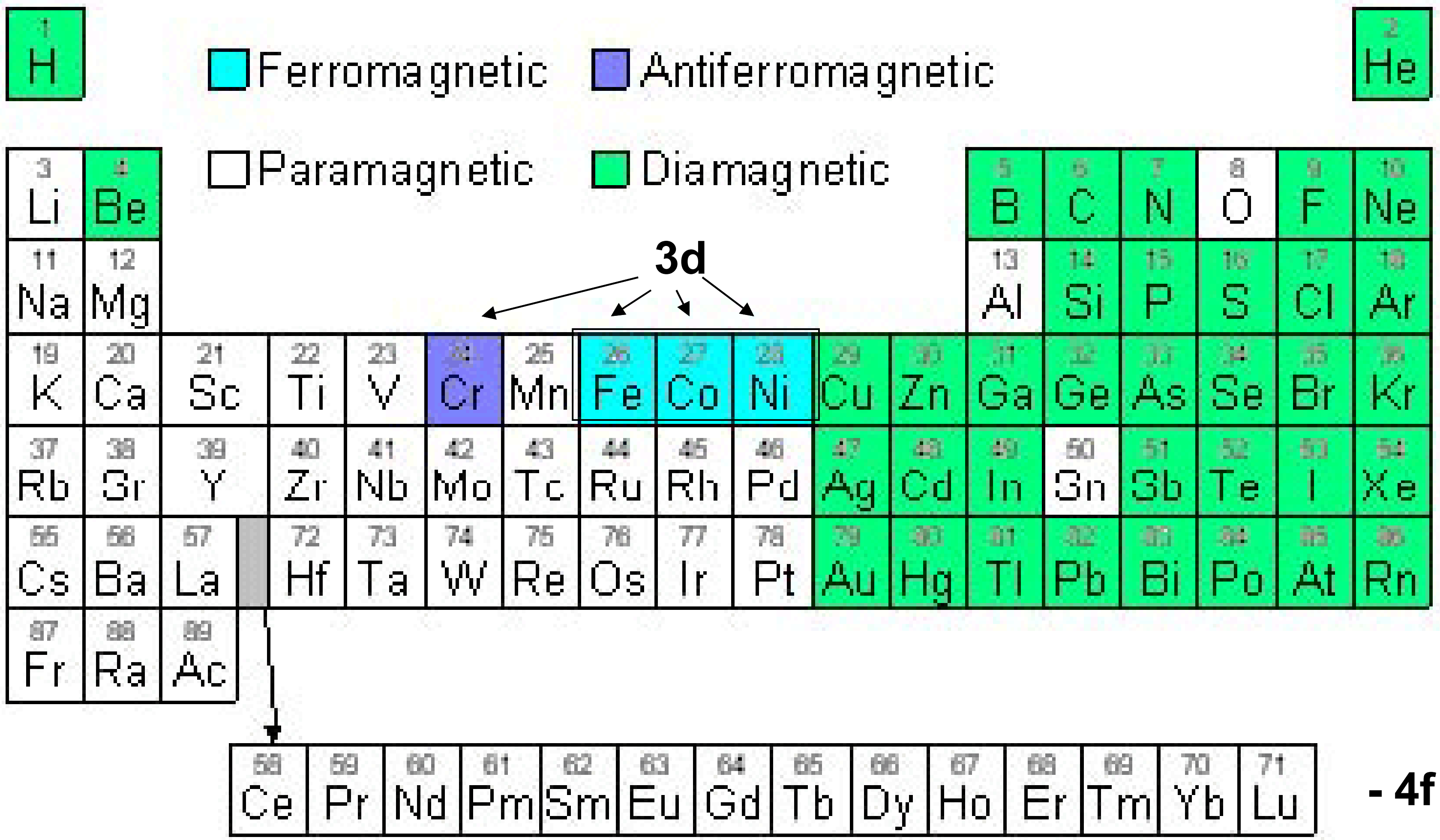
→ **Ferromagnetism** - When a ferromagnetic sample is placed near a magnet, it will be attracted toward the region of larger magnetic field. This is what we are most familiar with when our magnet picks up a bunch of paperclips

→Iron (**Fe**), cobalt (**Co**), nickel (**Ni**), gadolinium (**Gd**), dysprosium (**Dy**) and alloys containing these elements exhibit ferromagnetism because of the way the electron spins within one atom interact with those of nearby atoms

→The atomic magnetic moments align themselves, creating magnetic domains forming a ferromagnet. If a piece of iron is placed within a strong magnetic field, the domains in line with the field grow in size as the domains opposite to the field shrink in size

Magnetic Materials

ROOM TEMPERATURE



Magnetic moments

Elementary magnetic moments: atomic spin and orbital moments of 3d- and 4f-uncompensated electronic shells

For 3d-ions only spin S contributes to the magnetic moment

and **magnetic moment** $\boldsymbol{\mu} = -\gamma \boldsymbol{S}$

Total atom angular momentum J = L + S

For 4f-ions the spin S and orbital moment L form the total moment (strong spin-orbit coupling) and

Magnetic moment $\boldsymbol{\mu} = -\gamma \boldsymbol{J}$,

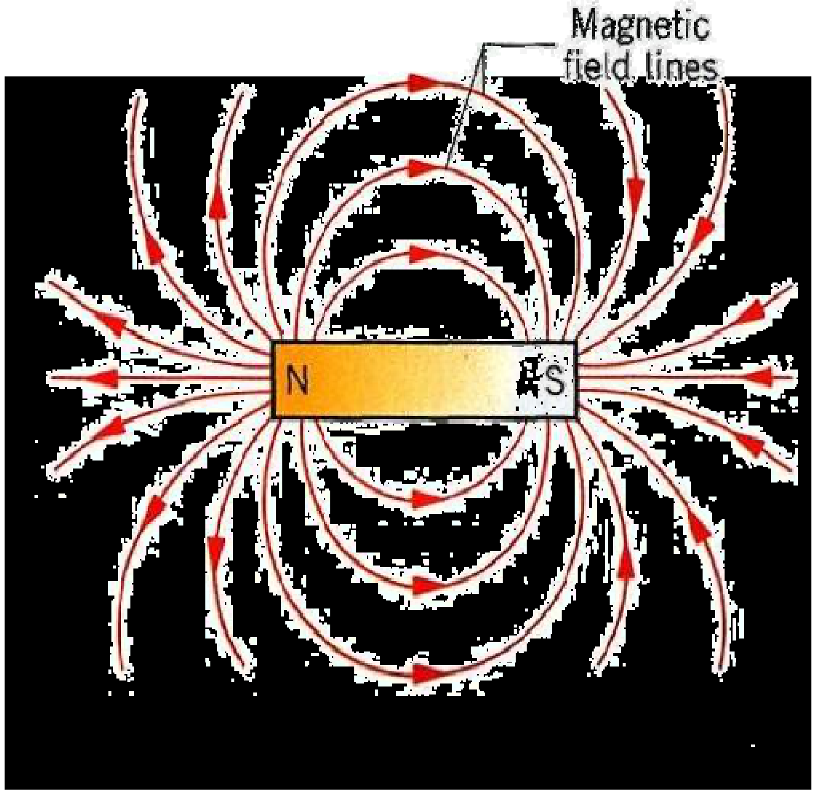
γ is the gyromagnetic ratio.
It depends on J, L, S

Magnetization $\mathbf{M} = \Sigma\boldsymbol{\mu}/V$

The Concept of "Fields"

M. Faraday, 1791-1867

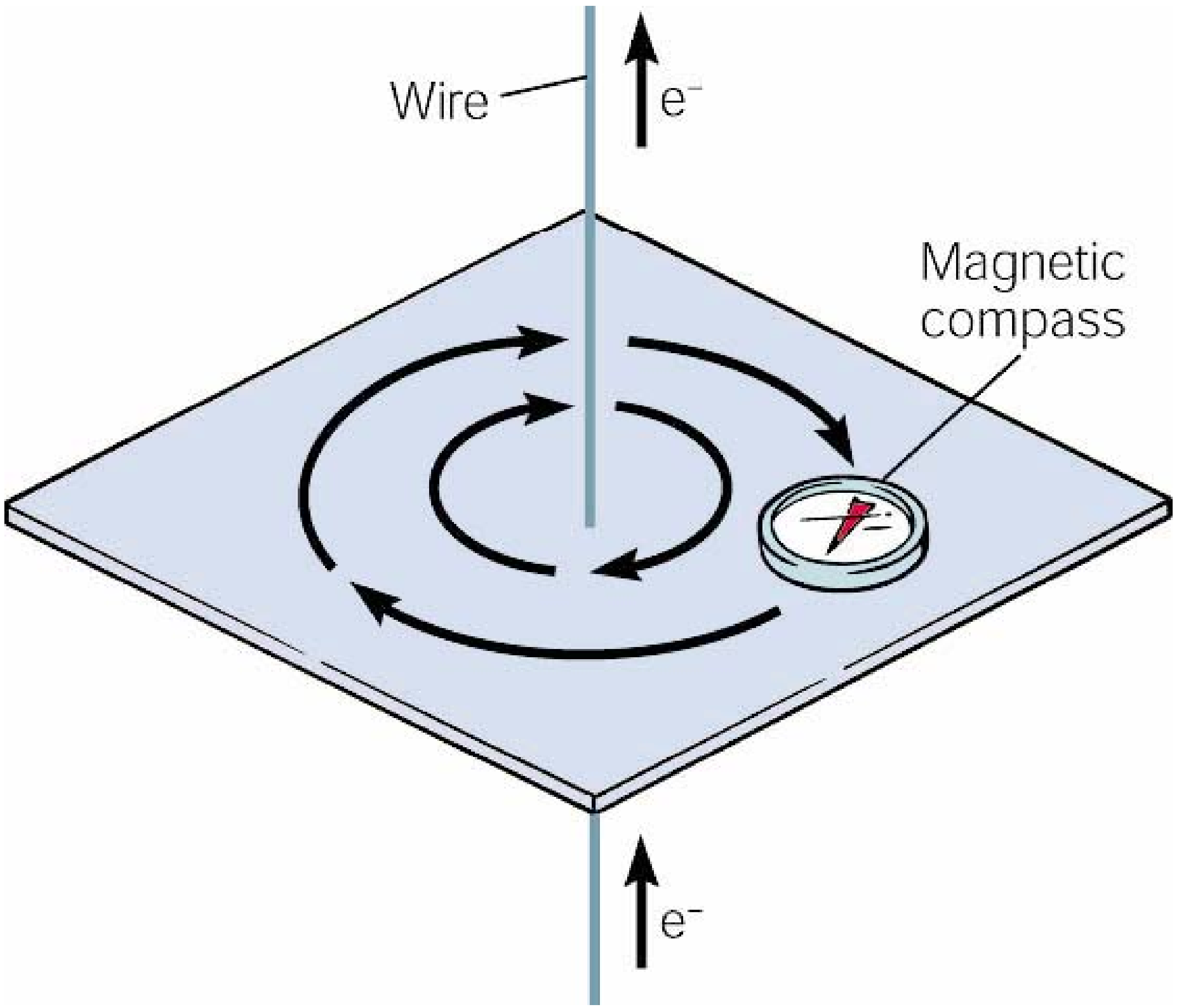
Michael Faraday realized that ...



A magnet has a 'magnetic field' distributed throughout the surrounding space

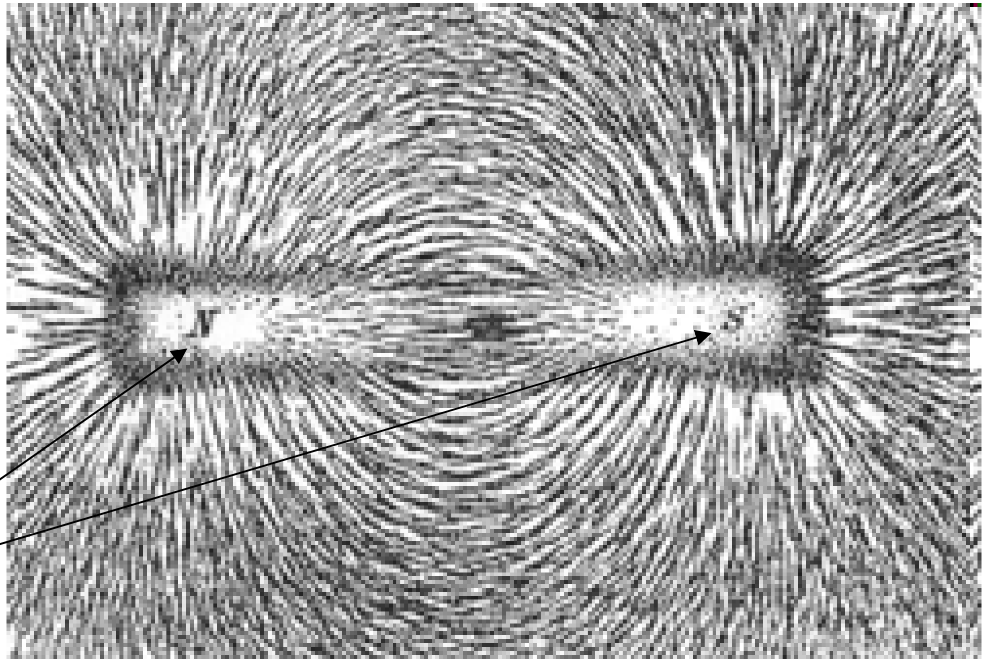
How can we feel the field?

A magnetic compass shows the presence and direction of the magnetic field around a straight length of current-carrying wire



Modern field sensors are based on resistance change in the presence of magnetic field (giant magnetoimpedance or anisotropic/giant magnetoresistance)

Magnetic poles and magnetic field



Magnetic
poles

Pairs of poles (N, S)

Single magnetic pole (monopole) has not been found…yet

Líneas de fuerza magnéticas de un imán de barra, producidas por limaduras de hierro sobre papel

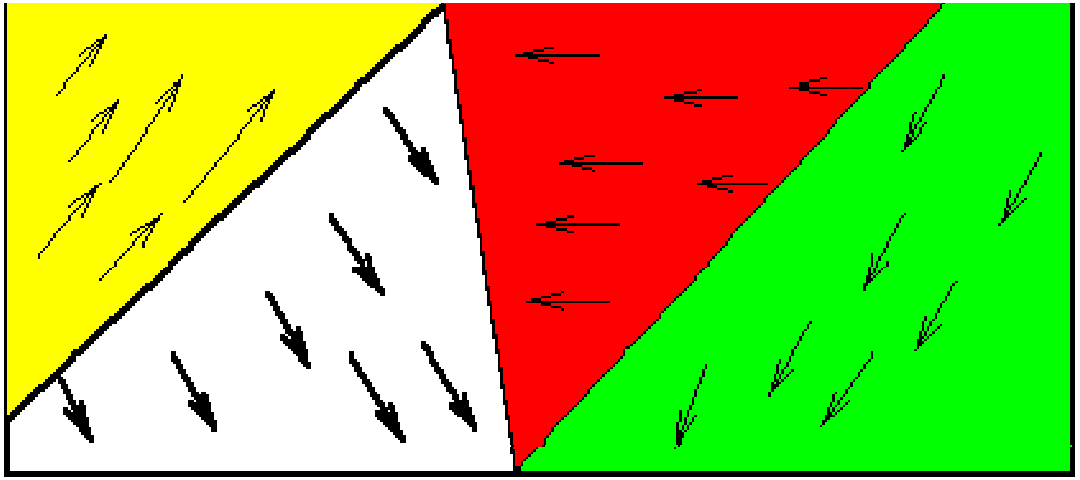
Iron filings are oriented in the magnetic field produced by a bar magnet along the field lines

Magnetic Field

- A force field similar to the electric and gravitational field, detected by a probe
- Force is experienced by the probe due to the field
- Sources of a magnetic field are magnetic poles
- Poles - fictitious points near the ends of a magnet

Why macroscopic magnet does not reveal magnetic field?

Magnetic domains

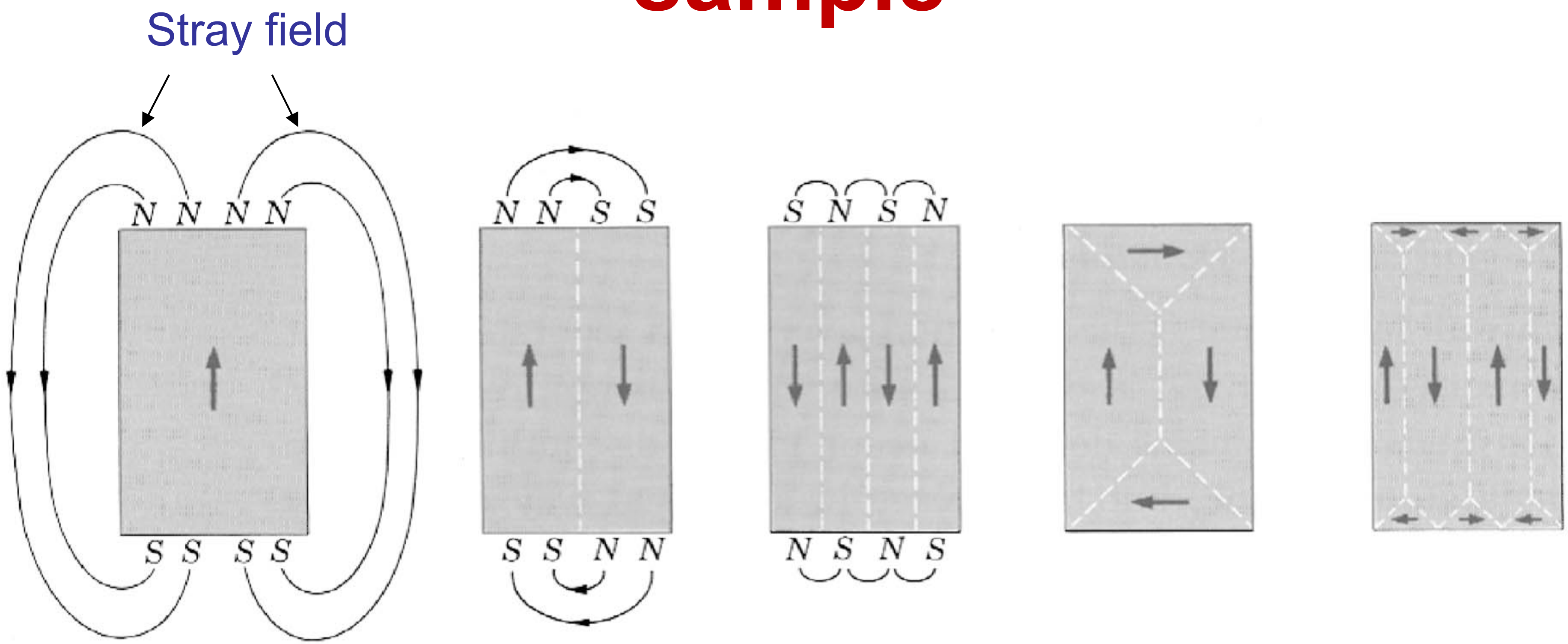


☆**Atoms themselves have magnetic properties due to the spins and orbital moments of the atom's electrons**

☆**Groups of atoms join so that their magnetic fields are all going in the same direction due to "exchange" interaction**

☆**These areas of magnetic atoms are called "domains" and transition regions between them are "domain walls"**

Domain structure of ferromagnetic sample

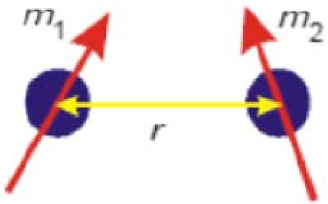


Magnetostatic energy is most effectively reduced for the last two structures.
The magnetic anisotropy “easy” axis is along vertical direction.

C. Kittel, 1948

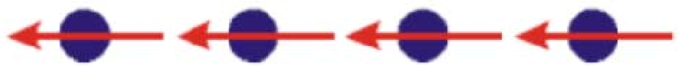
Magnetic interparticle interactions

Magnetic interactions

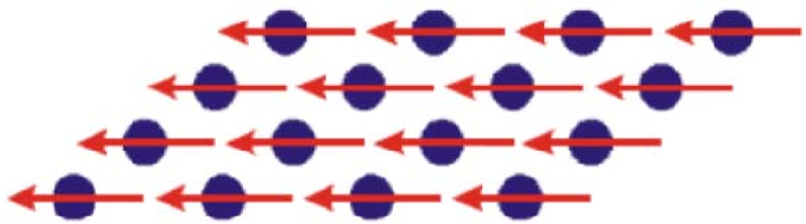


Exchange interaction : $E = -Jm_1 \cdot m_2$

Magnetic dipolar interaction: $E = \frac{m_1 \cdot m_2}{r^3} - \frac{3(m_1 \cdot r)(m_2 \cdot r)}{r^5}$



$J > 0$, ferromagnet



Shape anisotropy:

due to dipole interaction the spins in a film are „in-plane“

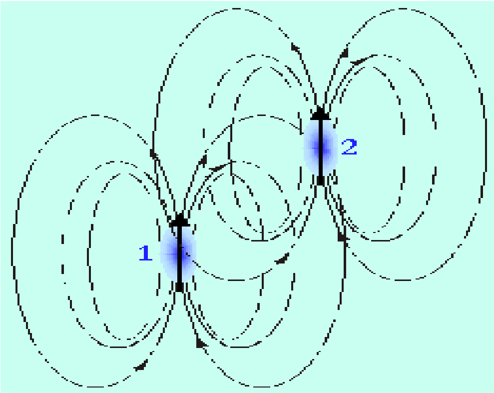
Zeeman energy : $E = -B \cdot m$

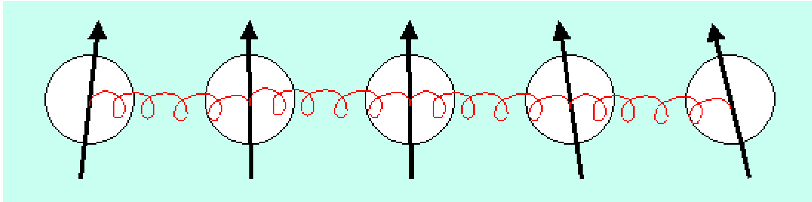
The exchange, dipolar, Zeeman etc. interactions form M distribution in a body

Magnetic energies –

interaction of magnetic moments

Magnetostatic

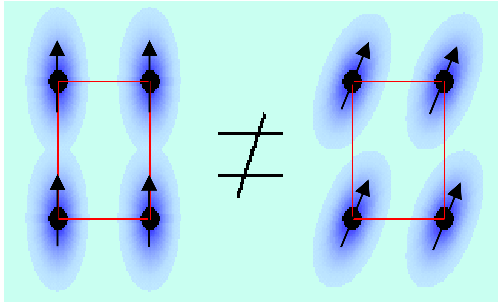




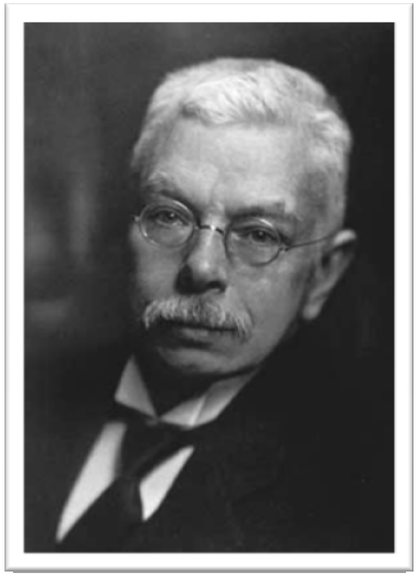
Exchange

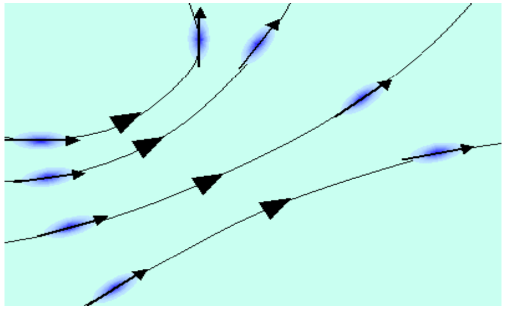
Nanomagnetism

Competition between different energies at the nanoscale will determine the fundamental properties of nanomagnets



Magnetocrystalline anisotropy





Zeeman

Pieter Zeeman **(1865-1943): splitting of spectral lines in magnetic field**

Nanomagnetism: artificial magnetic nanostrucures

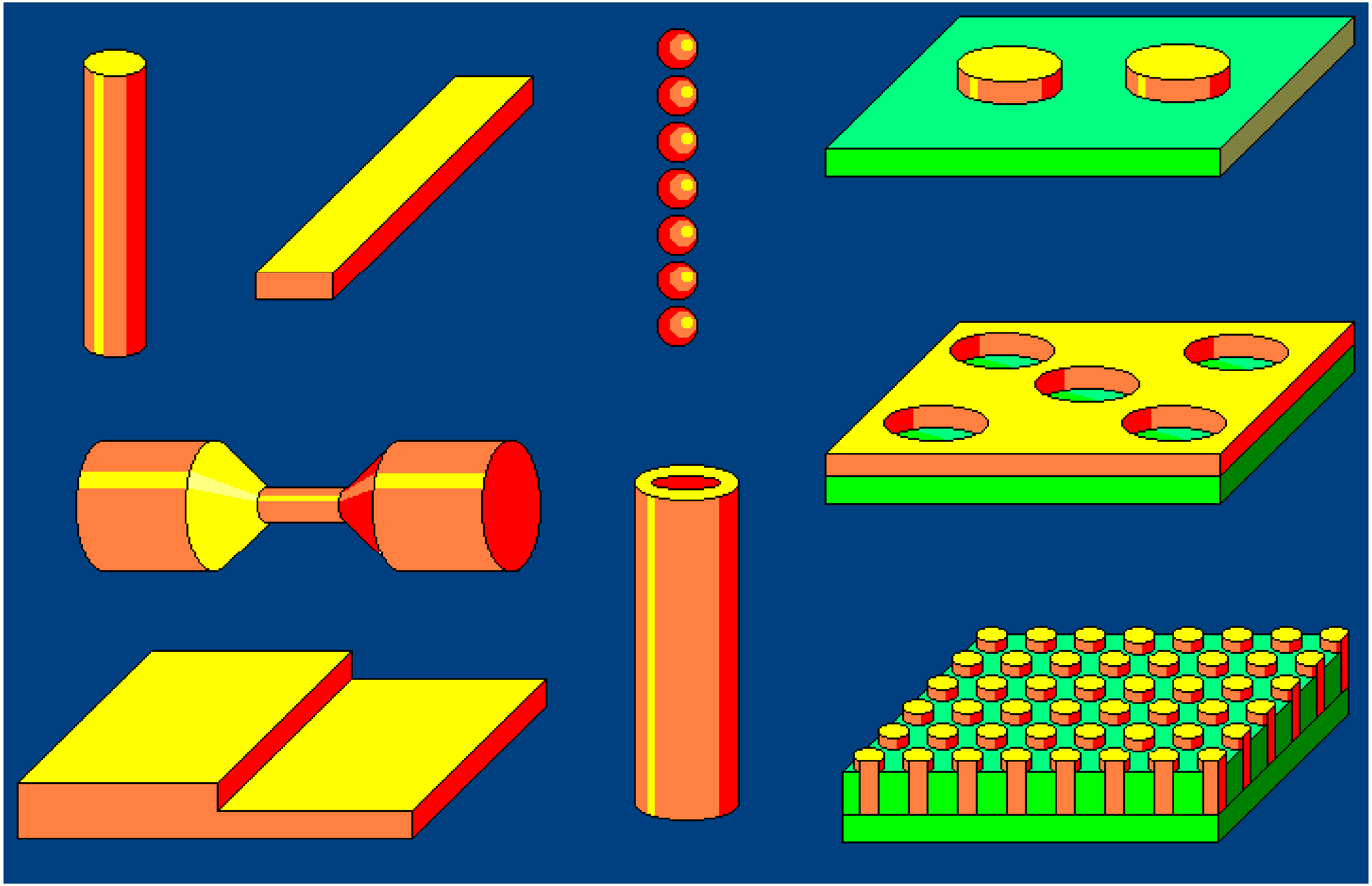
S. D. Bader, Rev. Modern Phys. 2006

Magnetic hard drives in computers

Applications of magnetism

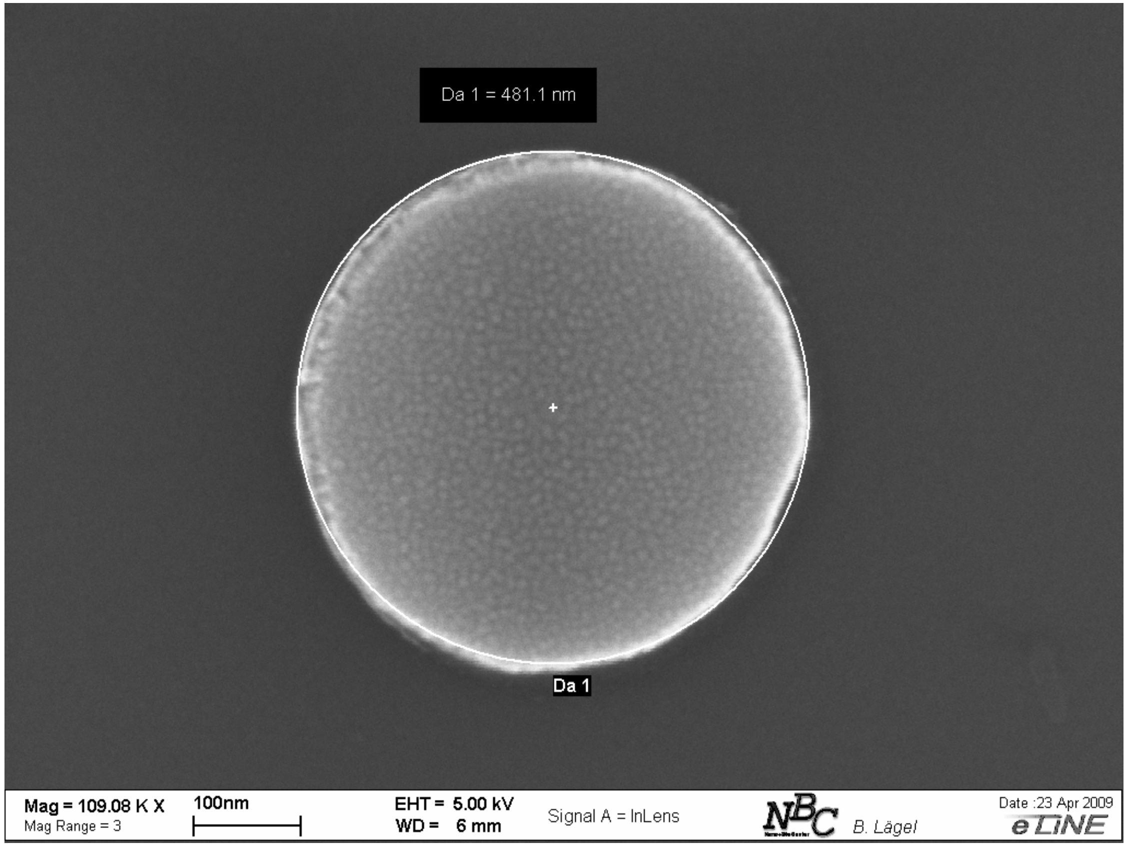
Hard disks record data on a thin magnetic coating
(information bits with different magnetization directions)

Patterned magnetic nanostructures



R. Skomski, J. Phys.: Cond. Matter 15, 841 (2003)

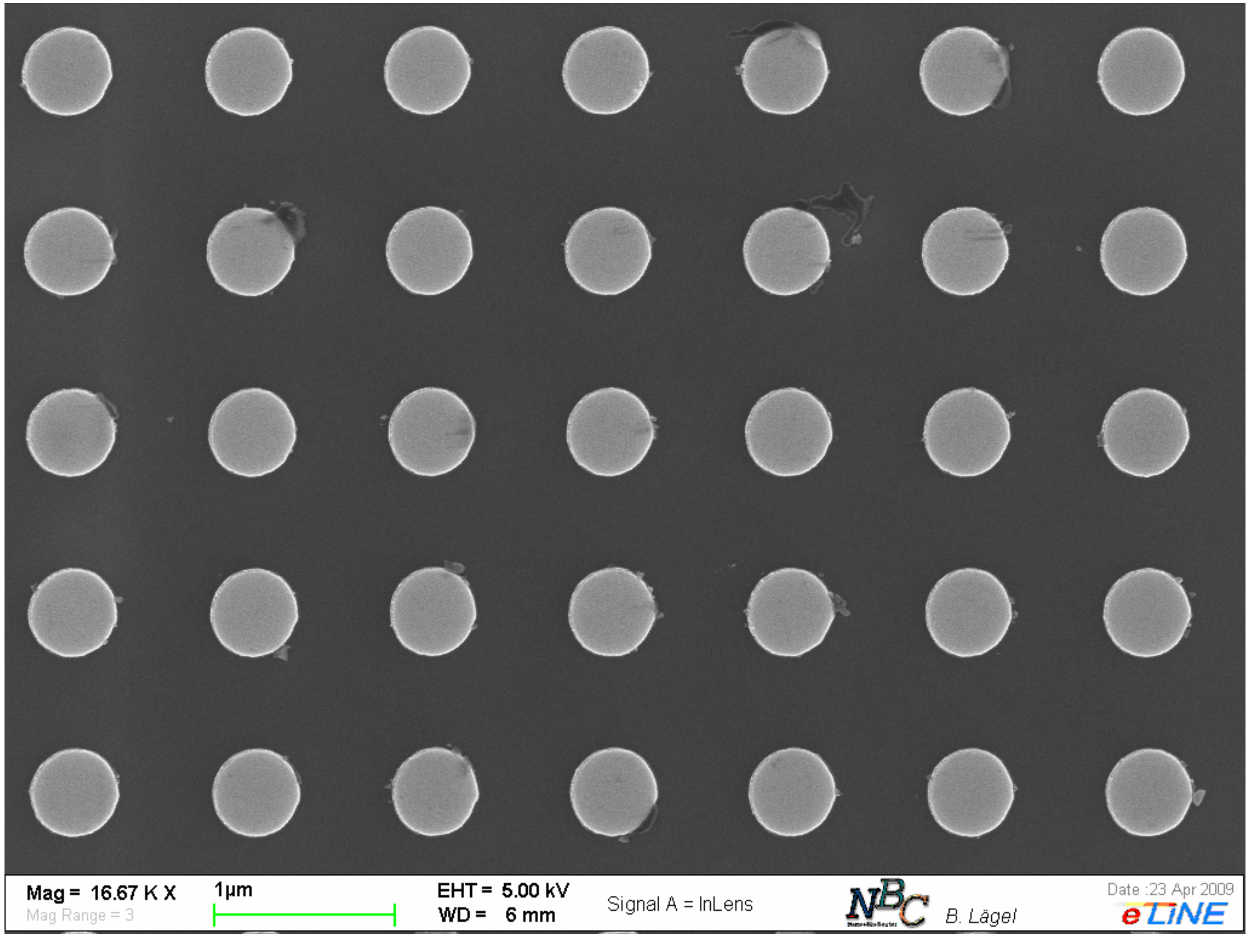
Examples of patterned nanostructures



Scanning electron microscope image of circular Permalloy dots with radius *R* = 240 nm and thickness *L*=40 nm

G. Kakazei et al., Appl. Phys. Lett. 2011

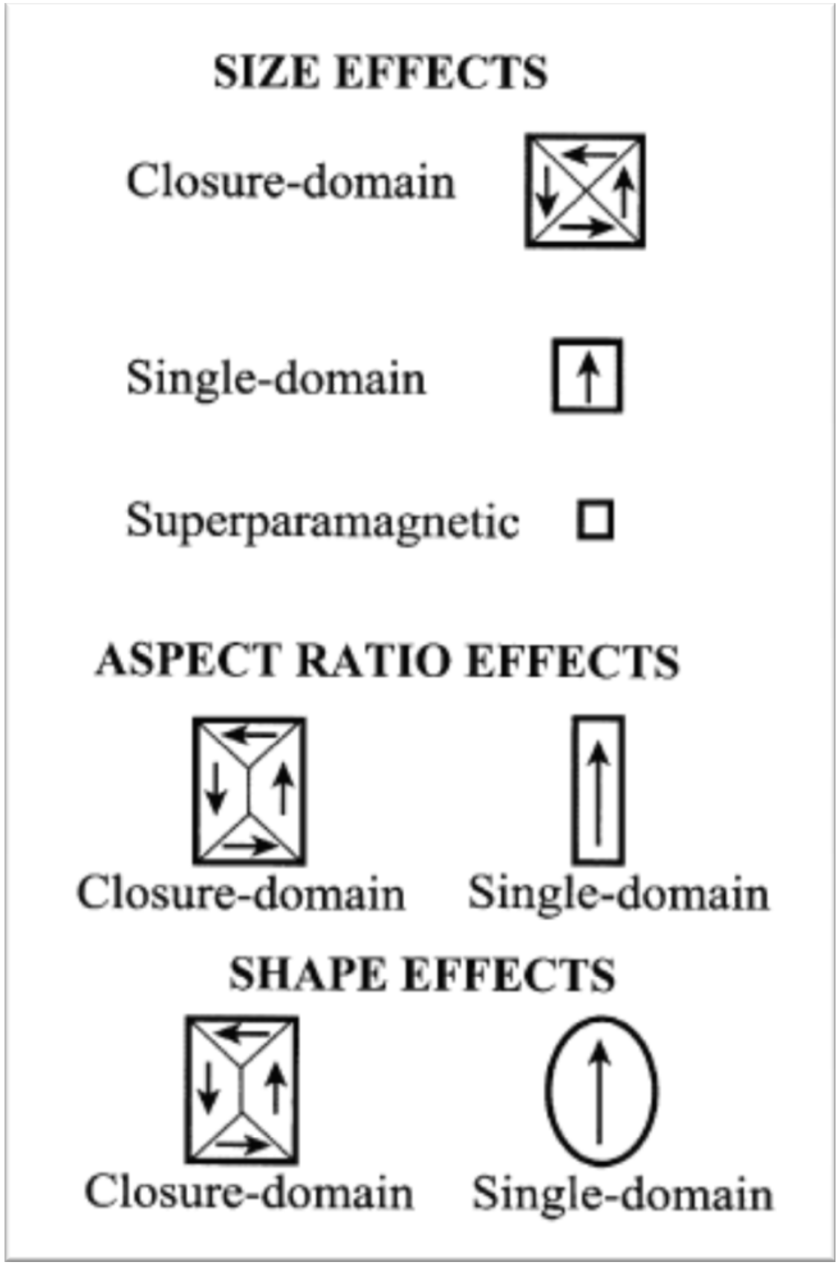
Examples of patterned nanostructures



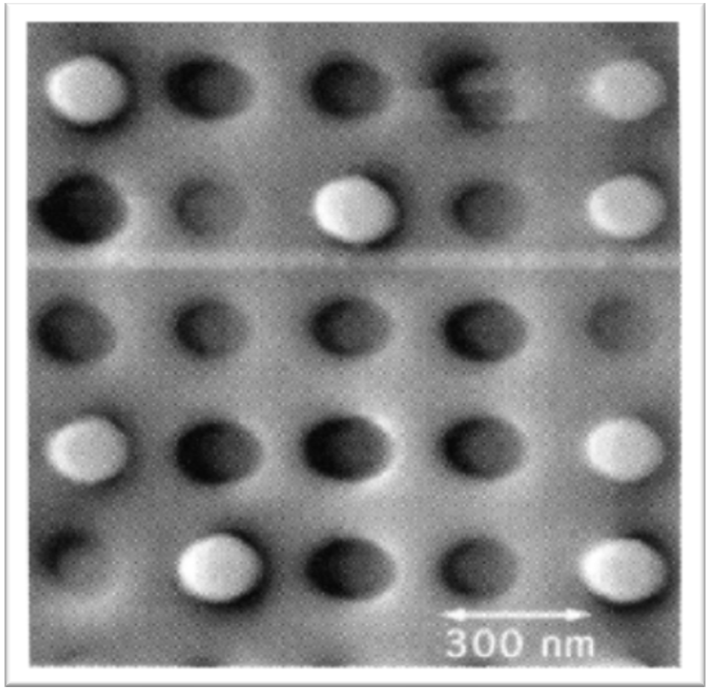
Scanning electron microscope image of the square array of circular Permalloy dots with radius *R* = 240 nm and thickness *L*=40 nm

G. Kakazei et al., APL 2011

Magnetic configurations in nanostructures



Schematic influence of size, aspect ratio and shape of a magnetic particle on the magnetization ground state

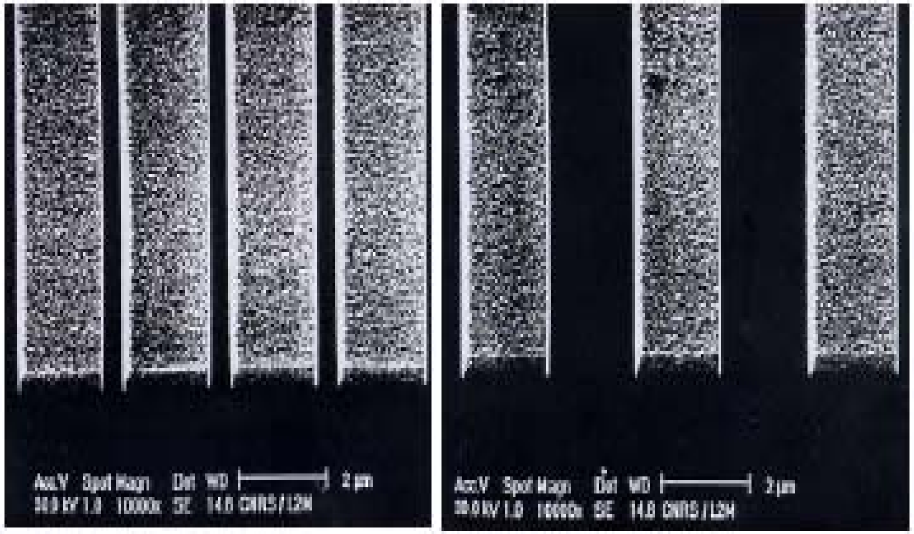


MFM image of Co dot array magnetized perpendicularly to the film plane (2R=70 nm, L=100 nm)

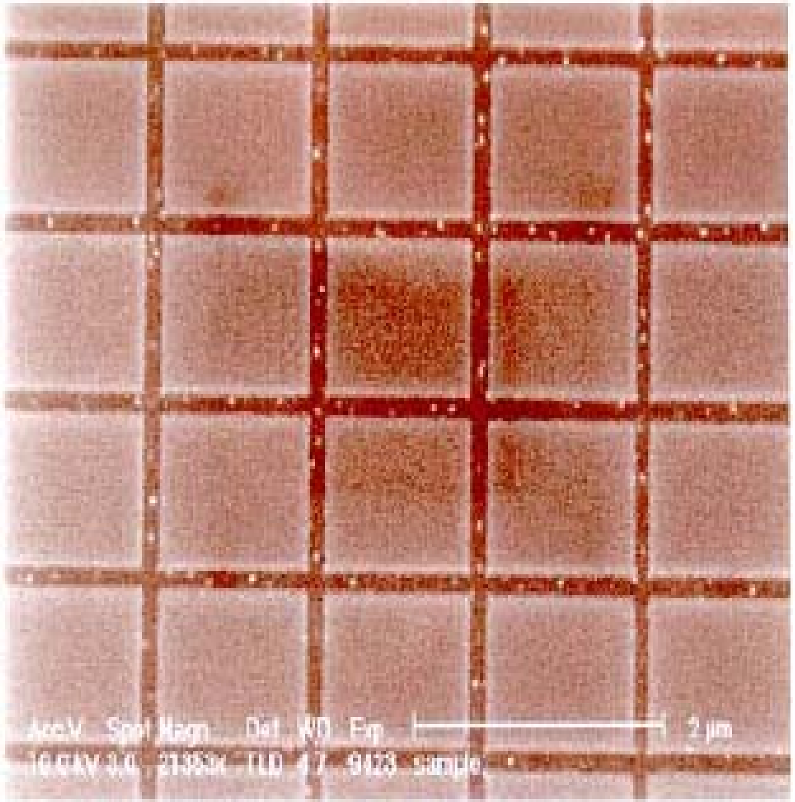
J. Martin et al., JMMM 2003

Examples of patterned nanostructures

Wires:

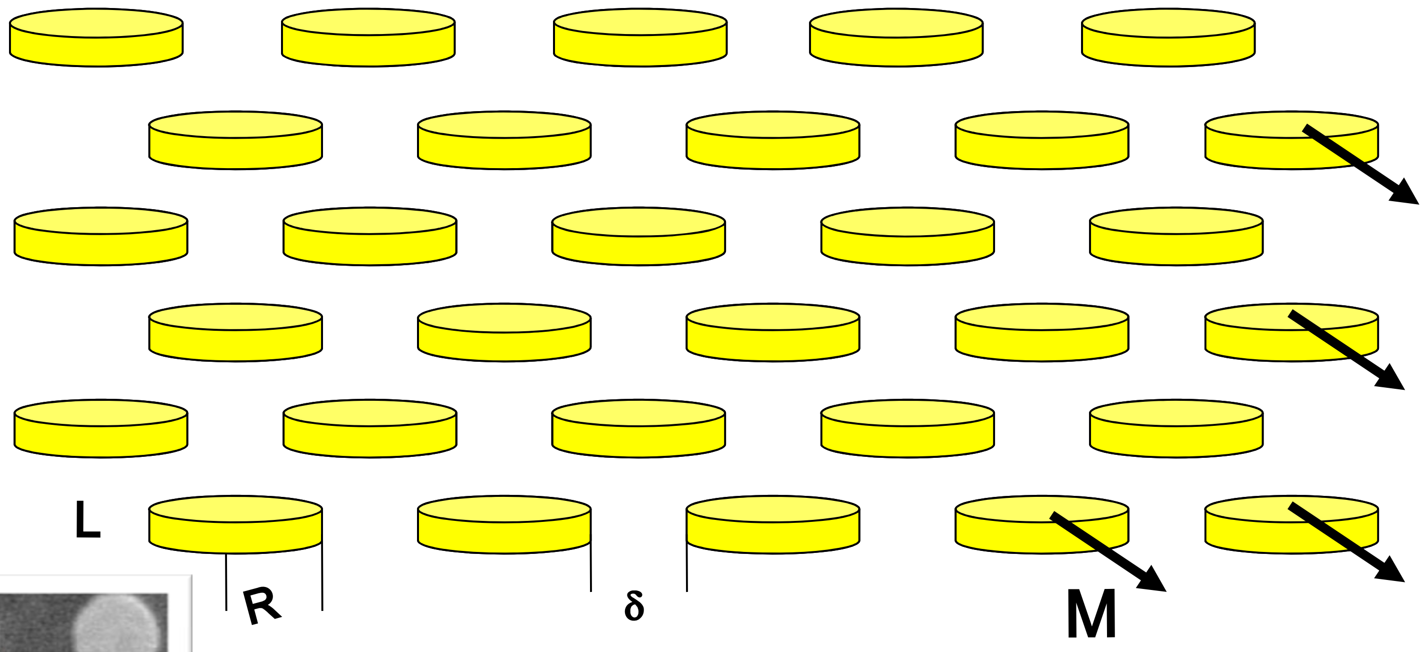


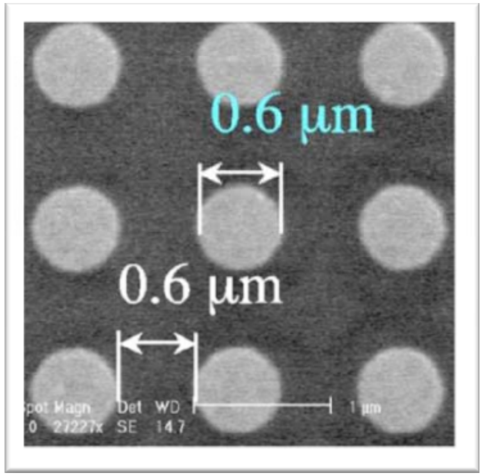
Dots:



The magnetic patterned structures are prepared by e-beam lithography

2D regular arrays of magnetic dots





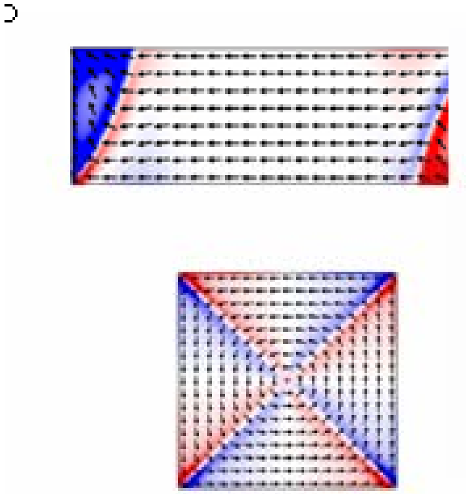
Dot radius R ~ 100-1000 nm
Dot thickness L ~ 10-50 nm

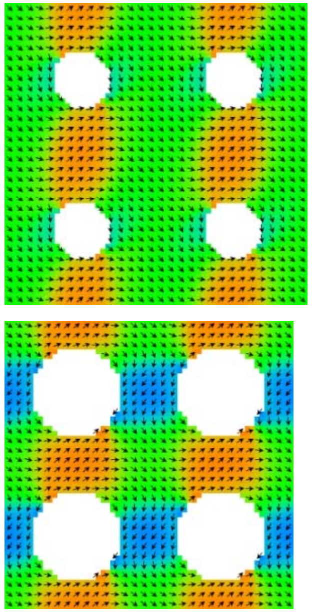
Small flat magnetic particle = magnetic dot

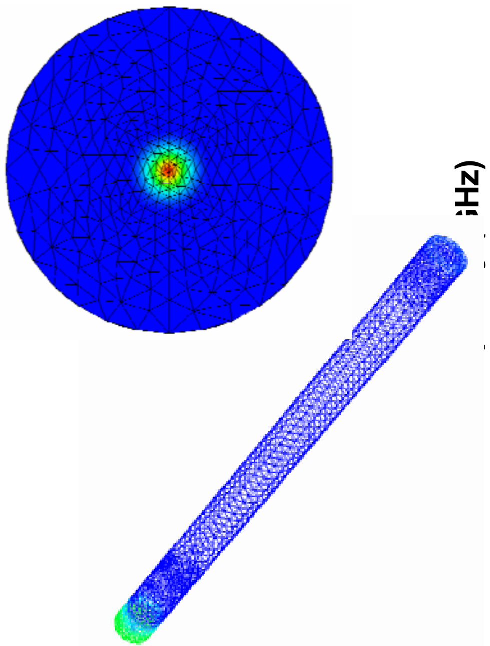
Magnetic nanostructures have dimensions comparable to magnetic correlation lengths: D ~ Lex, domain wall width

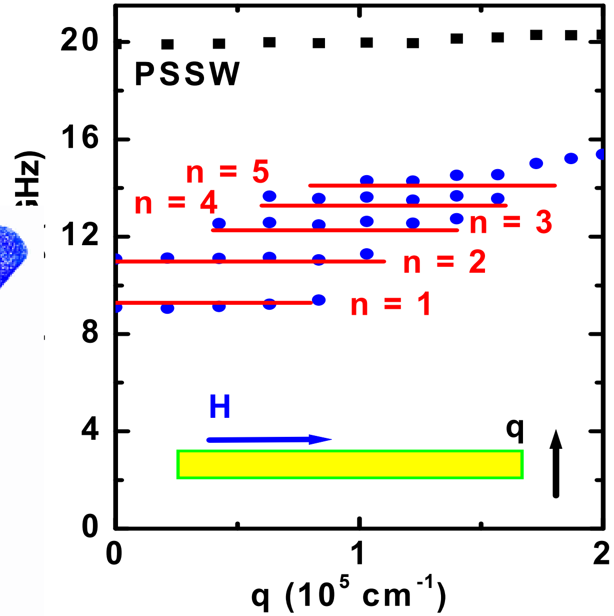
Novel phenomena due to competition between exchange and magnetostatic energies appear:

- Shape anisotropy & configurational anisotropy
- Magnetisation deviation at the corners and borders
- New magnetic states (vortices, “flower” and “leaf” states)
- Spin waves confinement and quantization





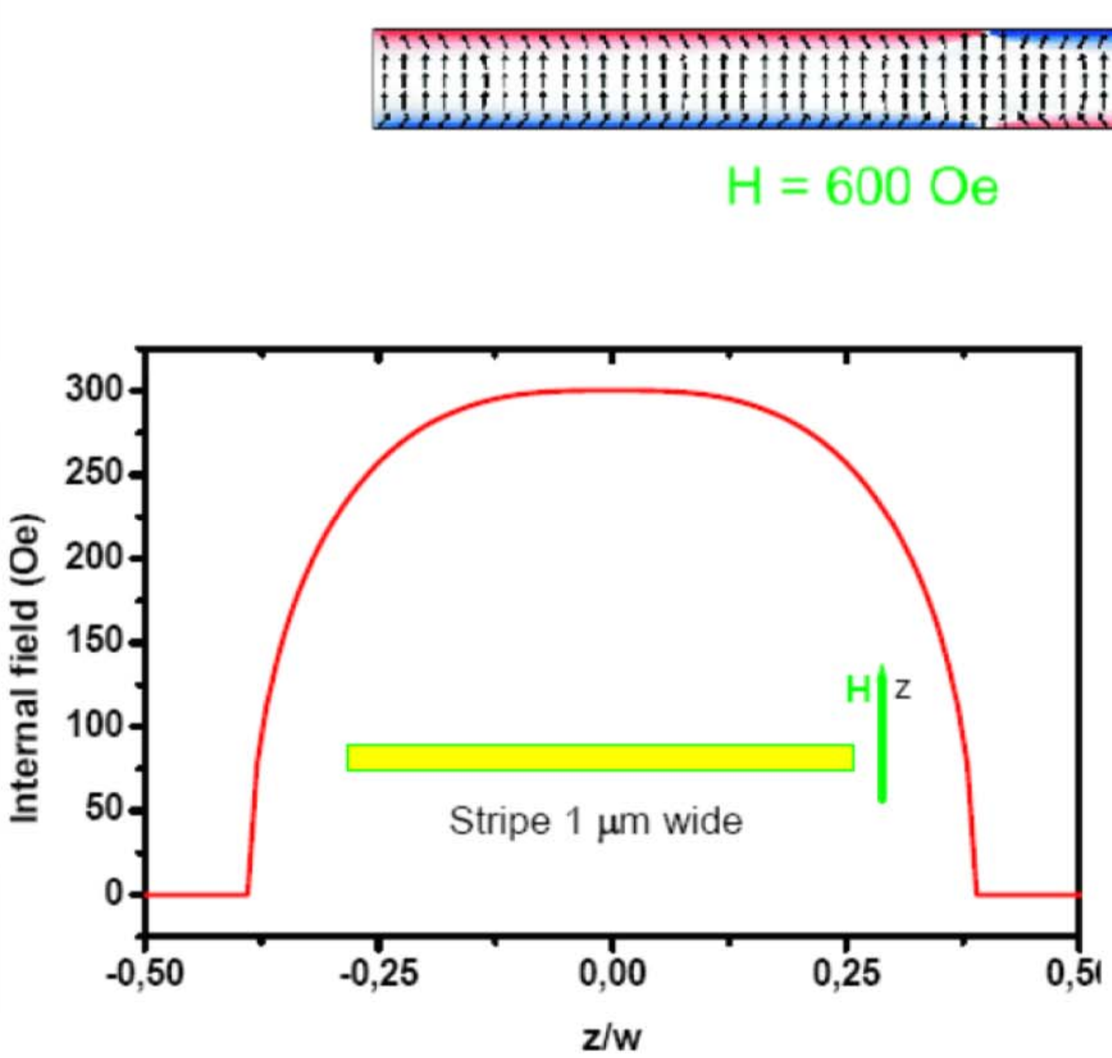




Poles avoidance principle:

M prefers to stay parallel to the sample borders to minimize magn. energy

Internal magnetic field distribution in stripe



Regions with canted magnetization and zero internal field are located near the edges of the stripe

Shape is important for considering the stripe spin excitations

How to observe M patterns in small particles

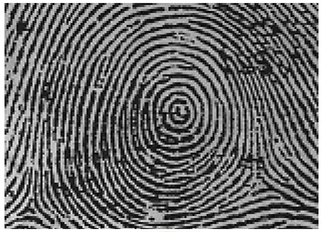
High-resolution magnetic microscopy

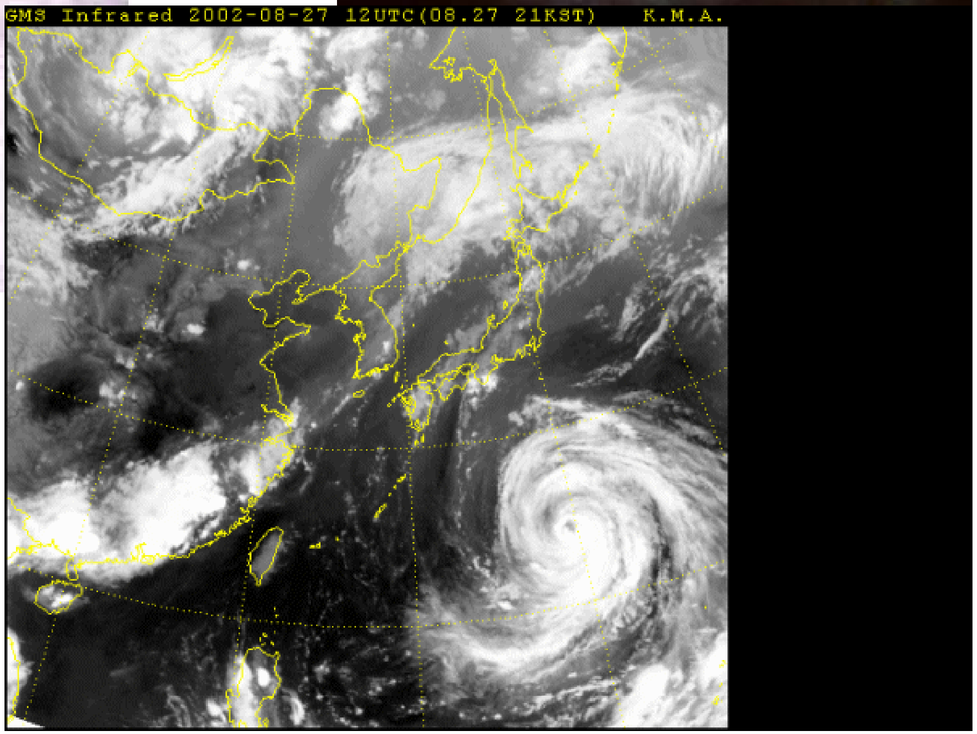
"Far-field" techniques	Spatial resolution	Temporal resolution	Magnetic fields	Element specificity
Electron microscopy (Lorentz, SEMPA, PEEM, SPLEEM)	<10 – 100 nm	ps … ms	limited	yes/no
X-ray microscopy	25 nm	ps	yes	yes
Magneto-optical microscopy (Kerr/Faraday microscopy)	300 nm	fs	yes	no

"Near-field" techniques				
Spin-polarized scanning tunneling microscopy (SP-STM)	1 nm	ms	limited	no
Magnetic force microscopy (MFM)	50 nm	ms	limited	no
Magneto-optical scanning near-field microscopy (SNOM)	50 nm	fs	yes	no

C. Back, 2009

Spiral Structures in Nature



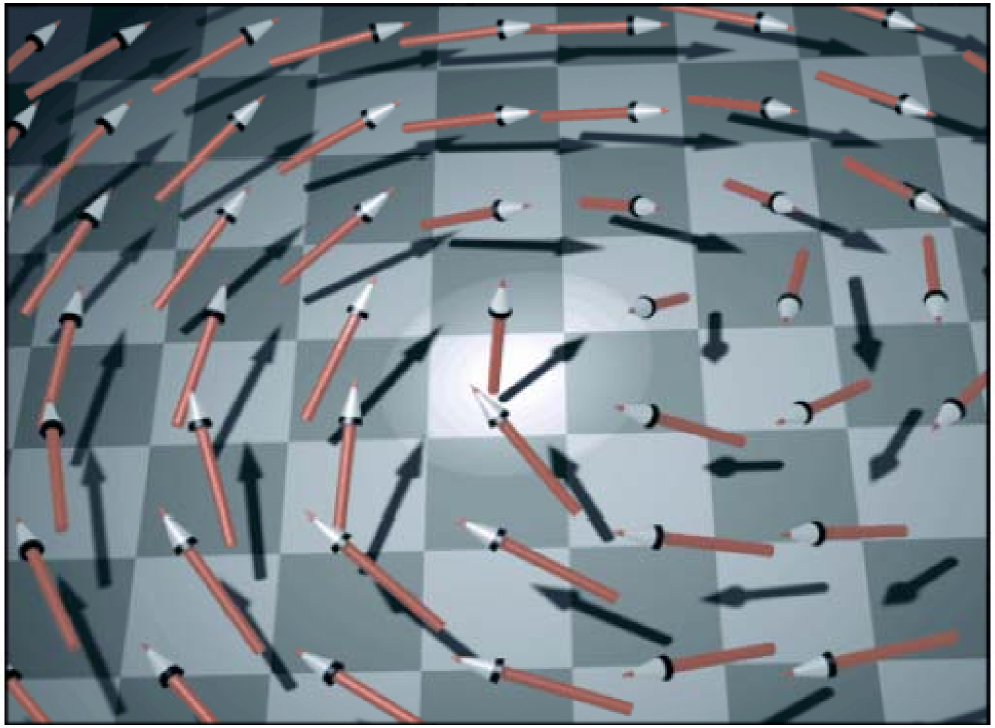


Typhoon Rusa (2002. 8.)

Fingerprints, tornados, typhoons, whirlpools, spiral galaxies

Spiral structure of magnetic moments = magnetic vortex

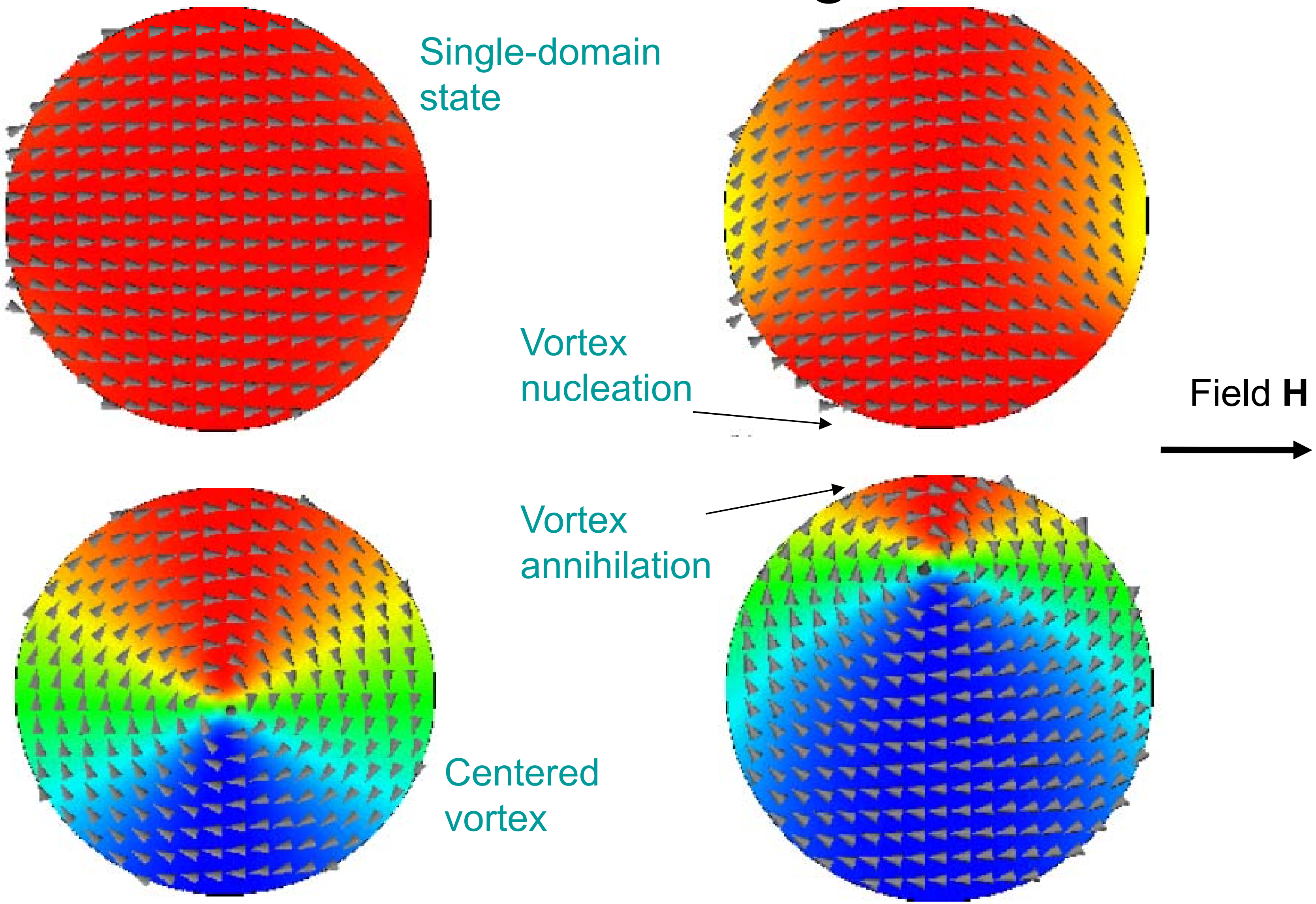
Vortex core: a close-up



M points <u>out of the plane</u> (↑ or ↓) at the core (≈10 nm).

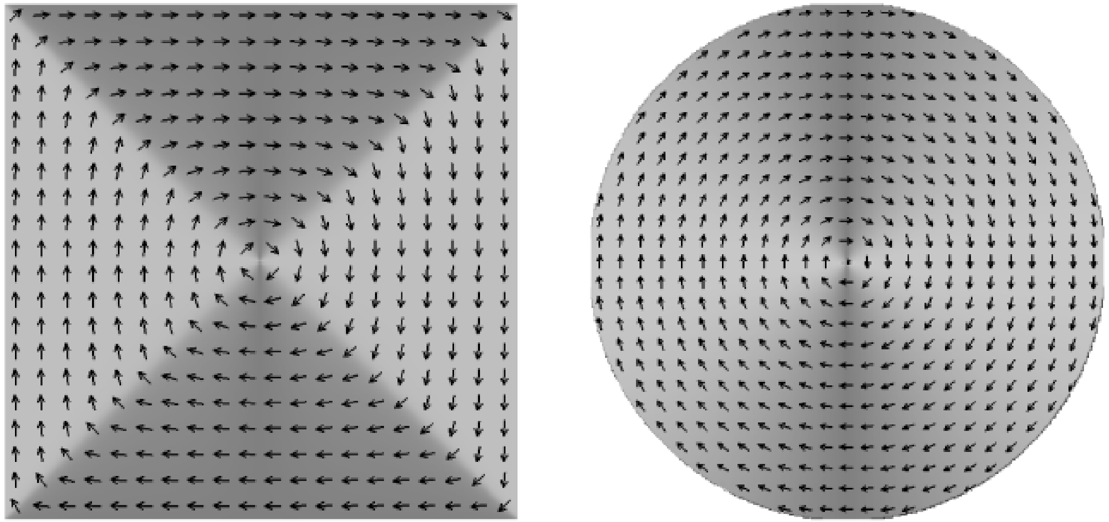
A. Wachowiack *et al.*, Science (2002).

Vortex state dot in magnetic field



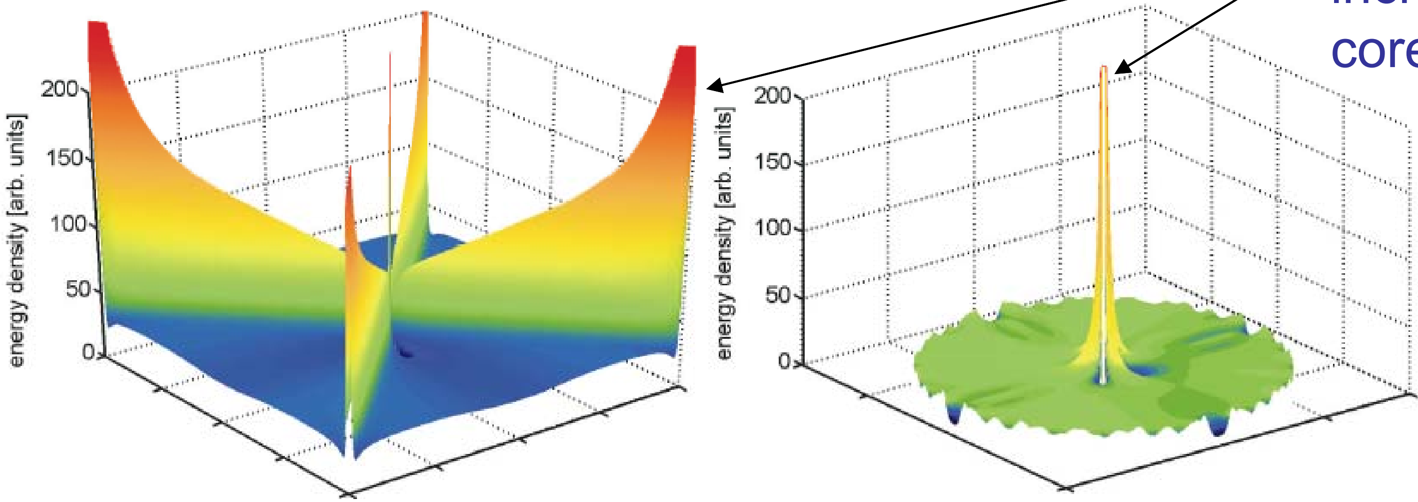
Simulations by W. Scholz, JMMM 2003

Energy landscape in square and cylindrical dots



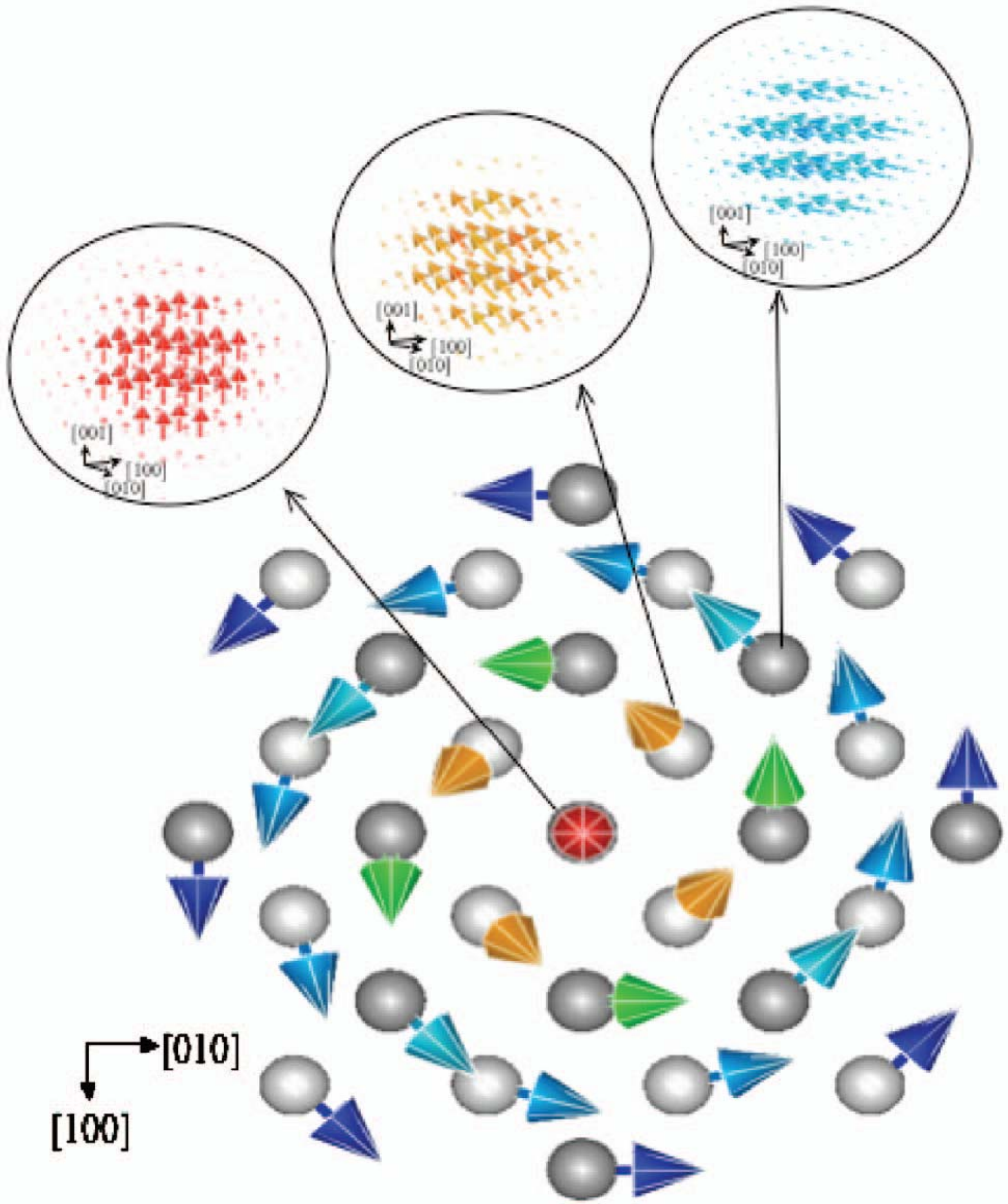
Magnetization
Vortex state

Eenergy density
increase in vortex
core/domain walls



C. Back

Magnetic structure of vortex core

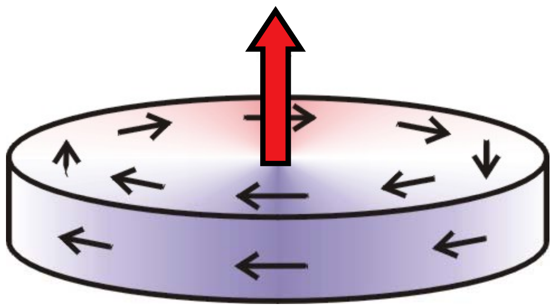


Nakamura et al.,
Phys. Rev. B, 2003

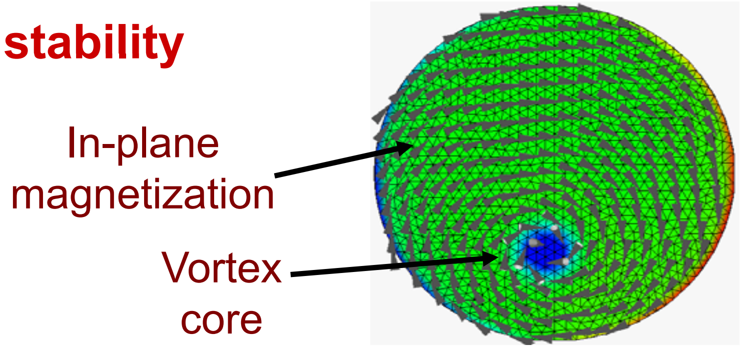
Spin arrangement of Fe atoms from electronic structure LSD simulations

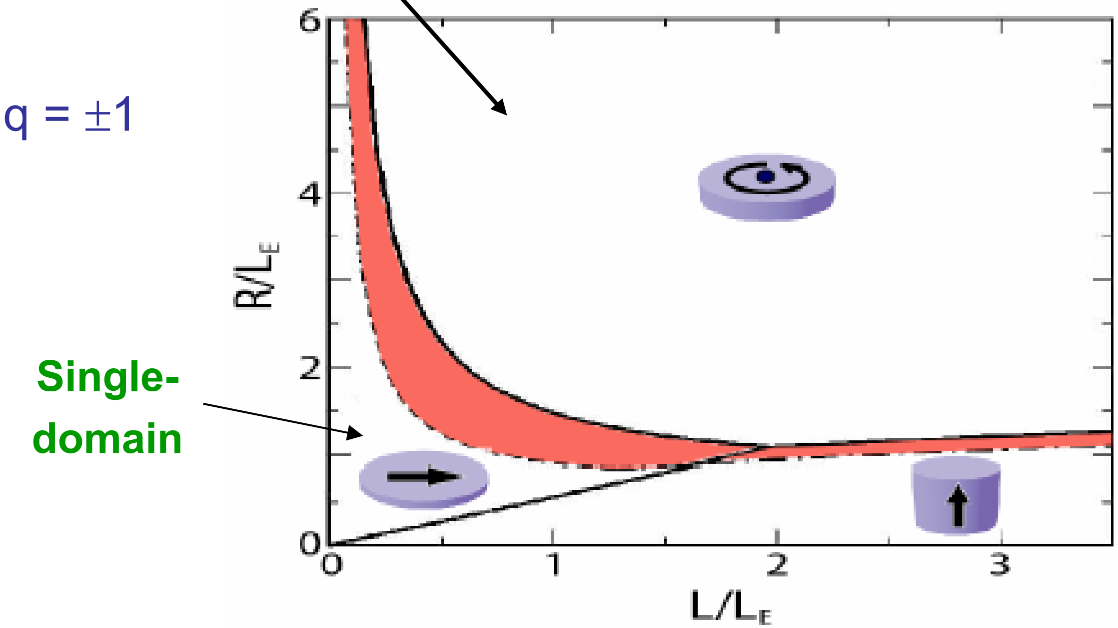
The spin of central atom is perpendicular to plane. The other spins form a curling (vortex) state

Magnetic vortices in soft magnetic dots



Magnetic vortex state stability





Magnetic Vortex Integers:

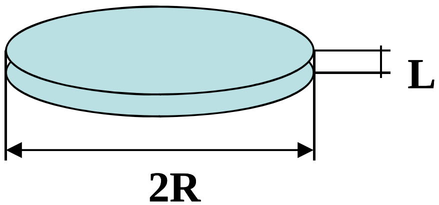
Vorticity (topological charge): $q = \pm1$

Chirality (CCW, CW): $C = \pm1$

Polarization: $p = \pm1$

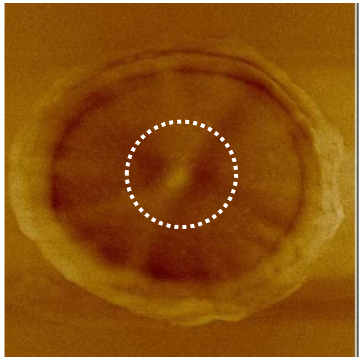
Magnetic ground state depends on:

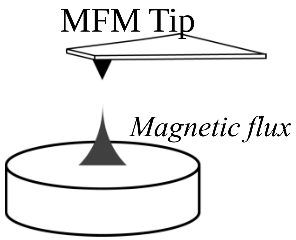
- Geometry: L and R
- Material: A and M_s



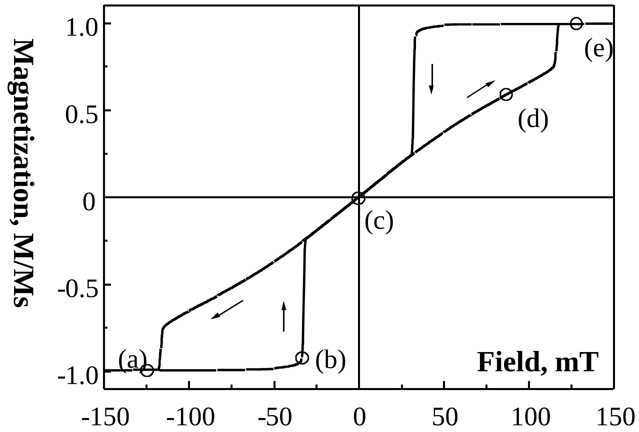
Phase diagram for magnetically-soft nanodots:
K. Metlov and K. Guslienko,
JMMM, 2002. Scale L_E=18 nm for FeNi

Magnetic vortices in soft magnetic particles (dots)



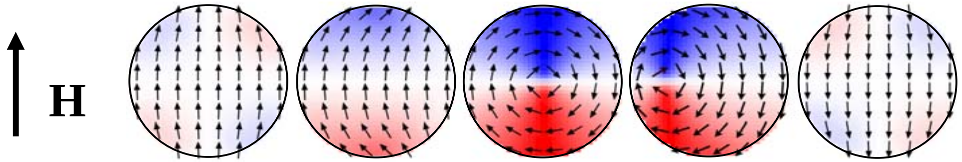


R ~ 100-500 nm
L ~ 10-50 nm



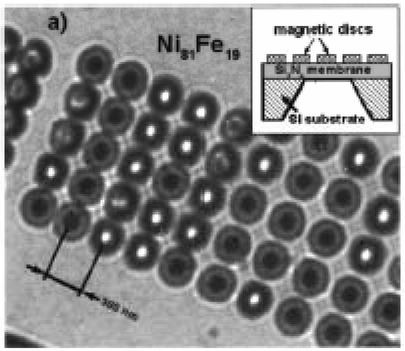
MFM image of magnetic vortex

Guslienko et al., PRB 2002

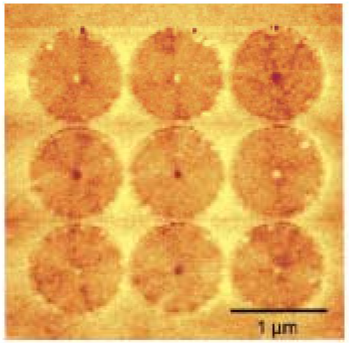


Magnetization reversal via vortex movement

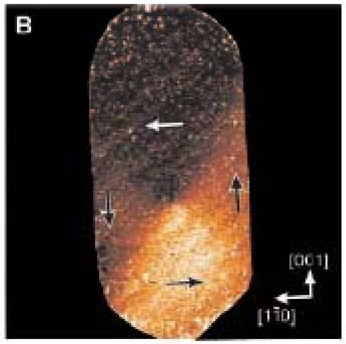
Experimental observation of magnetic vortices



1) Lorentz Microscopy on 200 nm Co disk



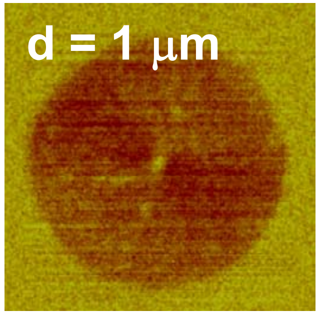
2) MFM on 1 µm Permalloy disk

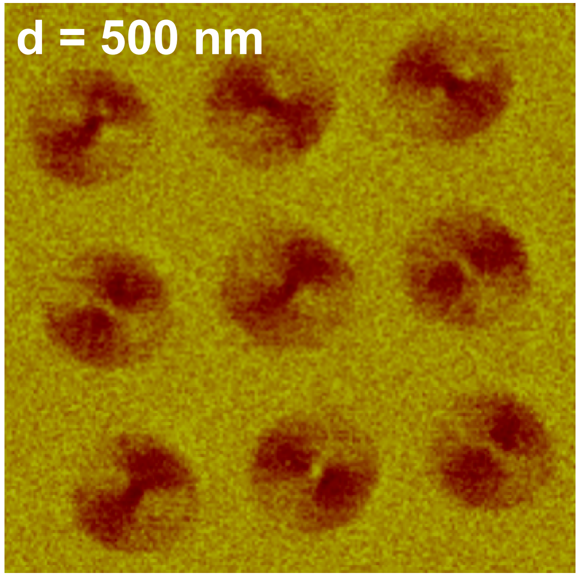


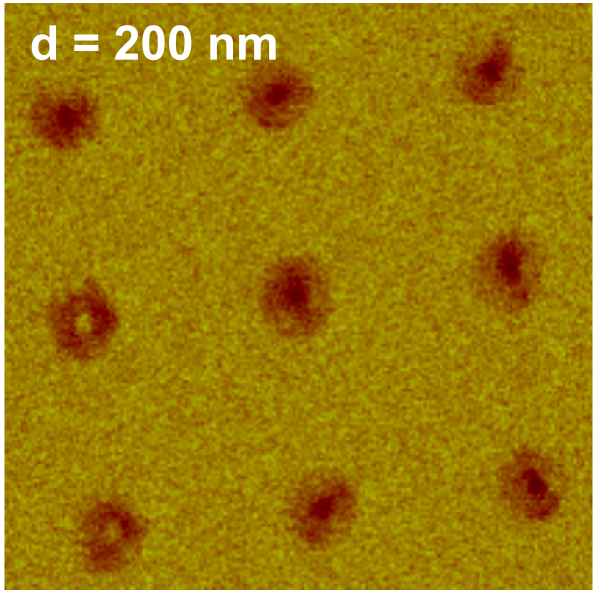
3) SP-STM on 200 nm wide and 500 nm long Fe island

1) J. Raabe *et al.* J. Appl. Phys. 88, 4437 (2000)
2) T.Shinjo *et al.* Science 289, 930 (2000)
3) A. Wachowiak *et al.* Science 298, 577 (2002)

Vortex-state excitations in circular dots (experiment)

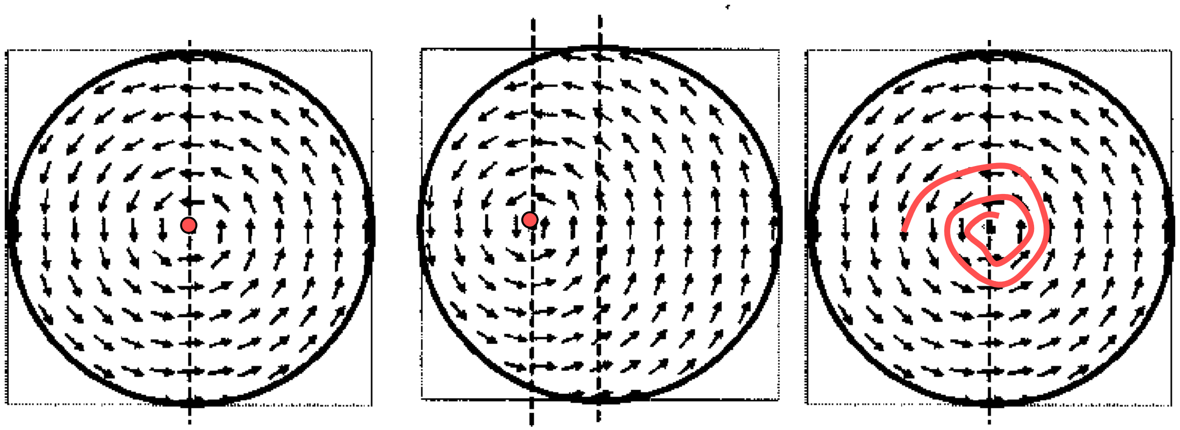






MFM Images:
Thickness = 60 nm
FeNi

Courtesy of P. Crowell



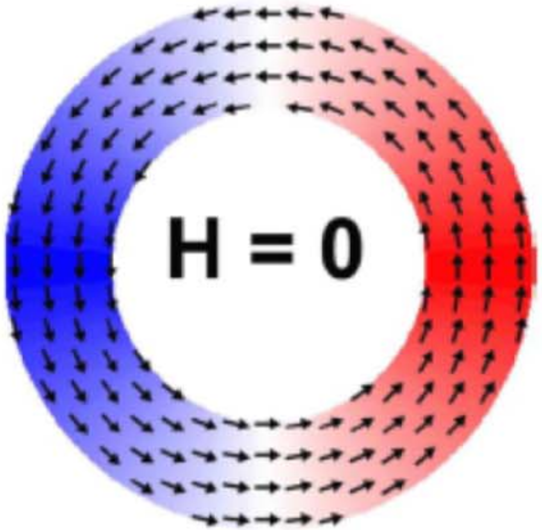
Guslienko *et al.*,
J. Appl. Phys. **91**, 8037 (2002).

$$\omega_0 = \frac{1}{2}\gamma M_S \frac{\xi^2}{\chi(0)}$$

About **1 GHz at L/R ~ 0.2**

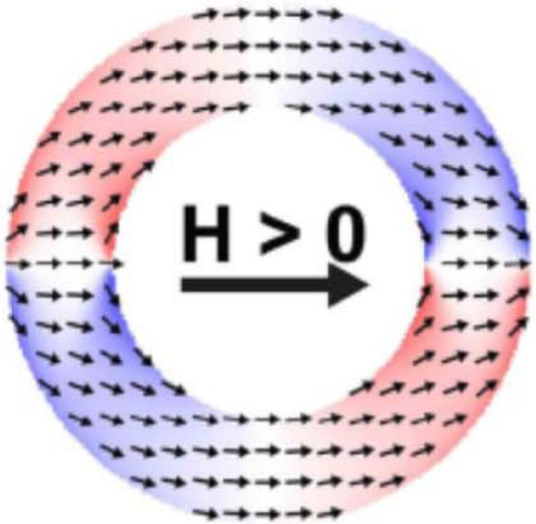
Magnetization distribution in rings

Vortex State



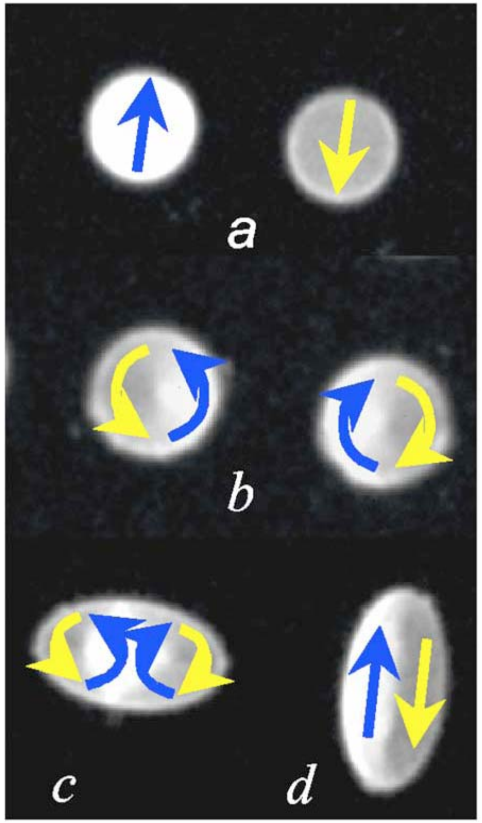
- rotational symmetry
- flux closure state
- no dipolar stray fields

Onion State



- broken symmetry
- effective surface charges at the poles
- strongly inhomogeneous internal field distribution

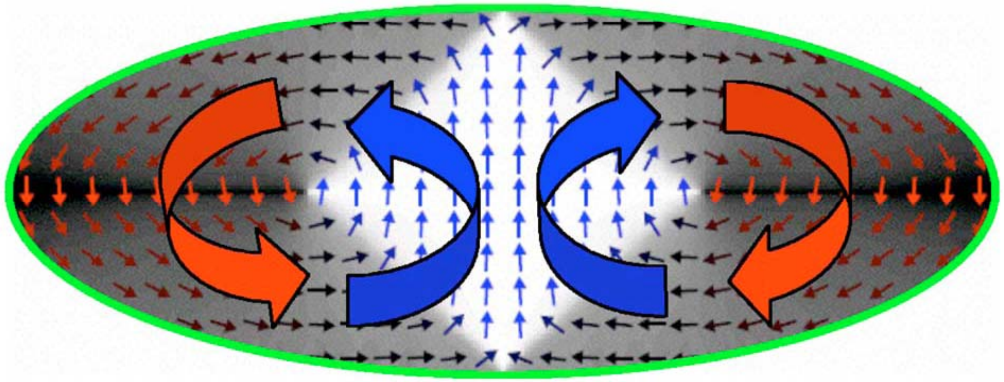
Single domain and vortex state FeNi dots



Patterned Permalloy structures

Different M images observed:

a) Single domain
b) Vortex
c) Double vortex
d) Double domain

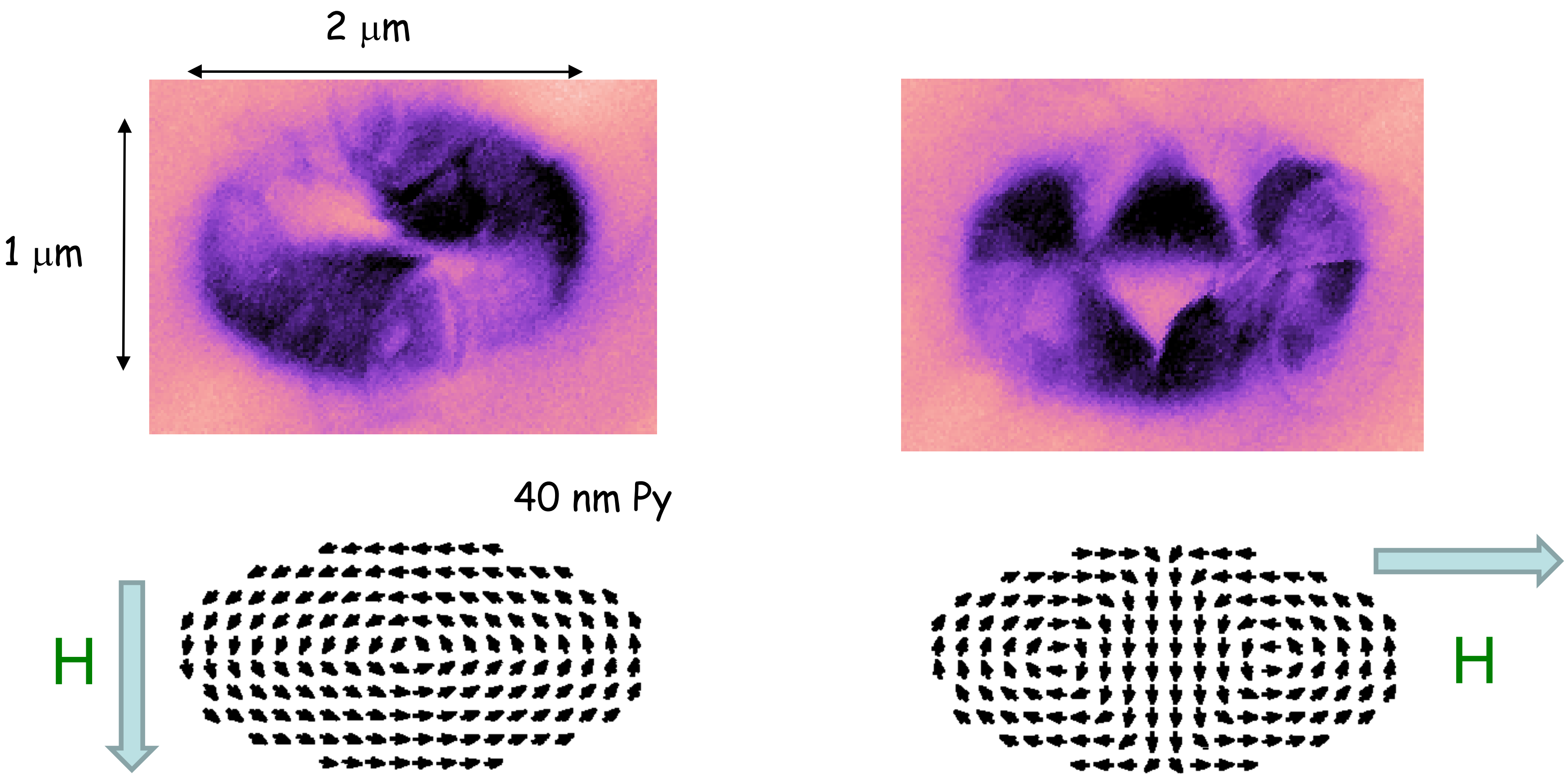


Micromagnetic simulation of image c)

- Double vortex state in elliptic dot

Elliptical Dots: Remanent States

- Magnetic force microscopy/micromag simulations



Single vortex

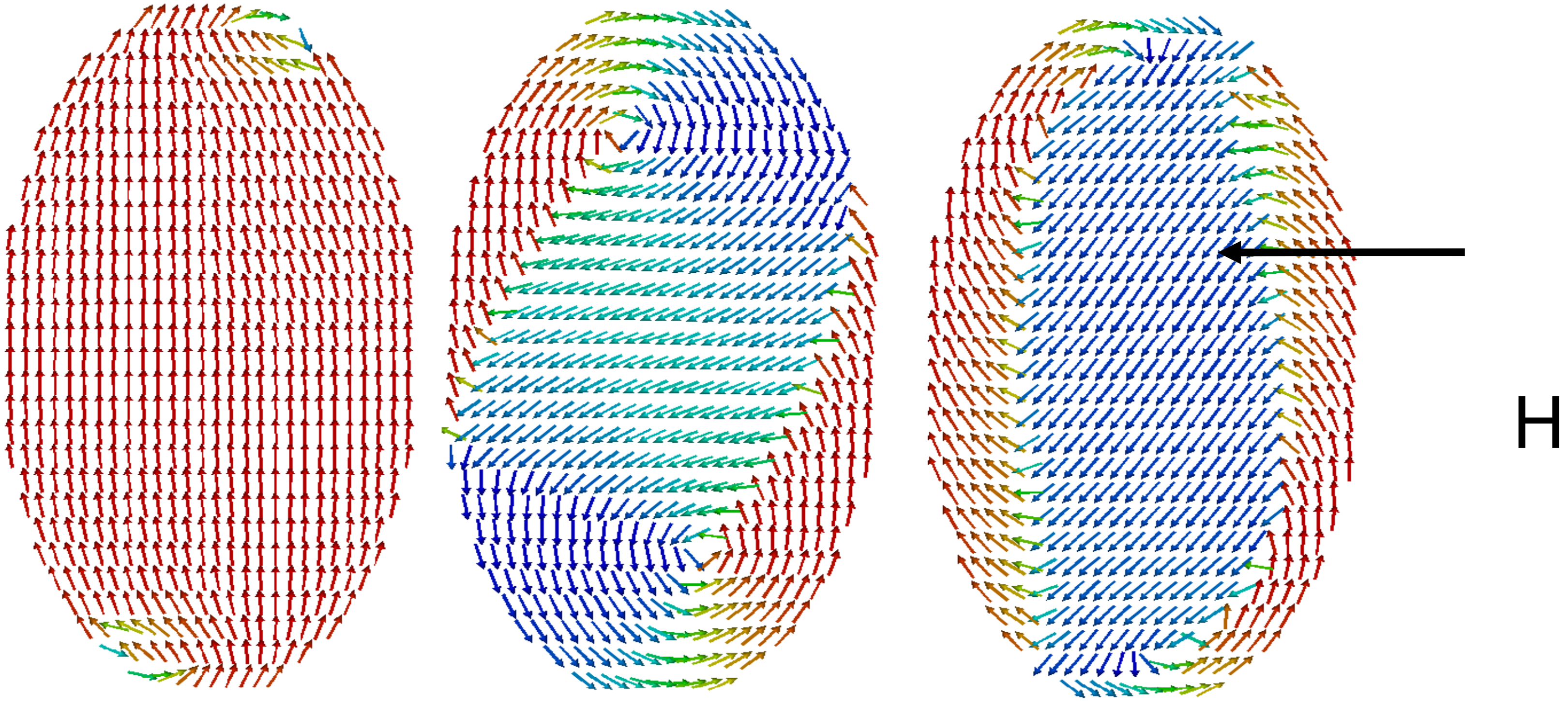
Double vortex

Vortex polarizations are up ↑ or down ↓

Static reversal of elliptical dots: Vavassori *et al.*, *PR B* 2004

Elliptic dots

Magnetisation reversal process: motion of vortices



- The magnetization reversal starts with nucleation of two vortices
- The reversal proceeds with two Néel-type domain wall propagation

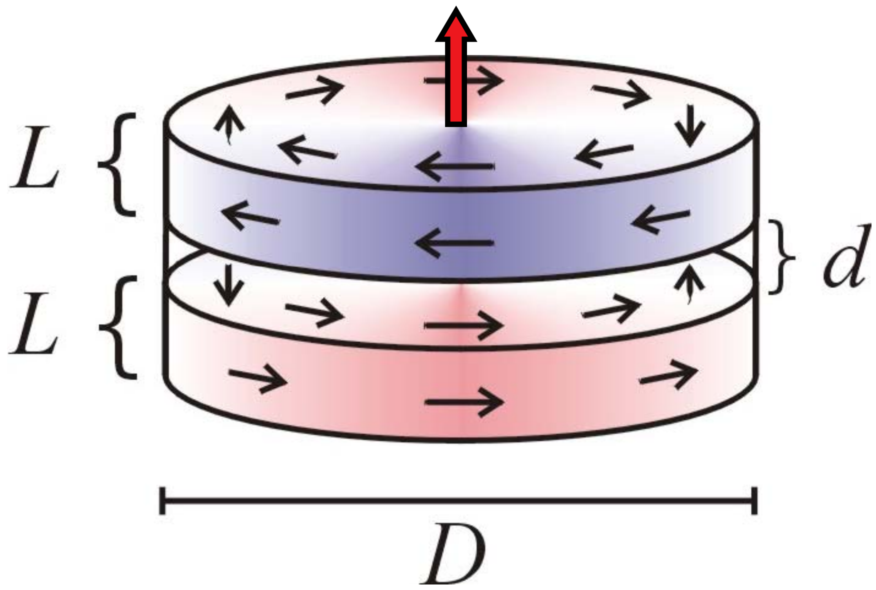
O. Chubykalo-Fesenko et al.

Tri-layer dots: quasi-spin valve structure

Magnetostatic interaction plays important role:

intralayer + interlayer

- Magnetostatic interactions between dots strongly affect the dynamic excitations
- Two vortex frequencies and complicated vortex core trajectories for tri-layer F/N/F dots



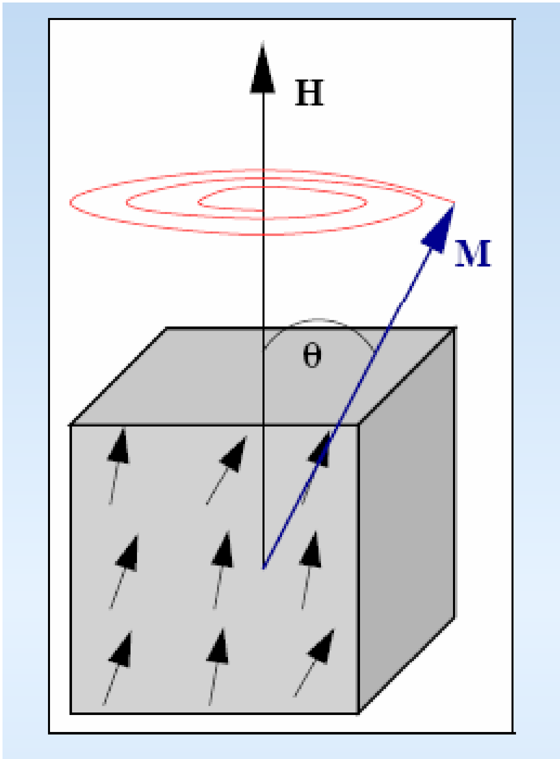
Two ferromagnetic (F) layers with nonmagnetic (N) spacer

Different polarizations and chiralities of F-layers

Guslienko et al., Appl. Phys. Lett., 2005

Basic principles of M calculations

- Magnetism is a quantum phenomena (spin and orbital angular momentum operators)
- Ab-initio calculations are not capable now to describe magnetisation dynamics at arbitrary timescale and temperature
- At larger spatial scale, relatively large magnetisation volumes (> 1 nm) can be considered as classical magnetic moments
- Statics and dynamics of classical magnetic moments can be described by the Landau-Lifshits equaion of motion
- The moments interact via exchange, dipolar etc. forces



Landau-Lifshits equaion of M motion

$$\frac{1+\alpha^2}{\gamma_0 M_S}\frac{d\mathbf{m}}{dt} = -\mathbf{m}\times\mathbf{h}_{\text{eff}} - \alpha\mathbf{m}\times(\mathbf{m}\times\mathbf{h}_{\text{eff}})$$

$\mathrm{m} = \mathrm{M}/\mathrm{M}_S$. - reduced magnetization,
Ms is saturation magnetization

α is the Gilbert (1955) damping parameter

γ is the gyromagnetic ratio (γ/2π ≈ 2.9 MHz/Oe)

h_eff is the effective field containing contributions from exchange, magnetostatic, Zeemann etc. energies

Lev Landau (1908-1968):

The equation of magneization motion was published in 1935 and was used in many research works afterwards

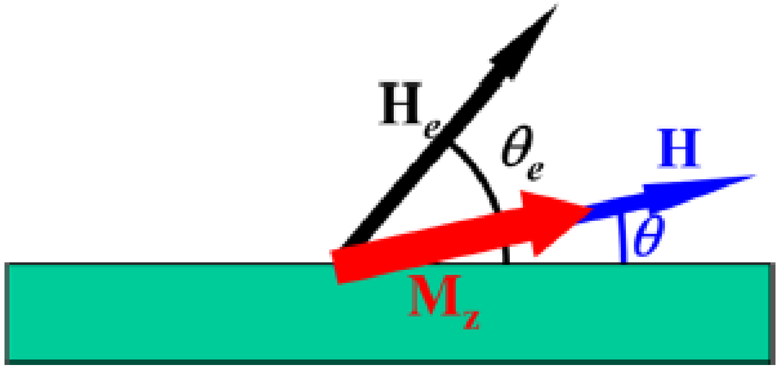
Magnetostatic Maxwell Equations

$$\nabla \cdot \mathbf{H}_d(\mathbf{r},t) = -4\pi\nabla \cdot \mathbf{M}(\mathbf{r},t)$$

$$\nabla \times \mathbf{H}_d(\mathbf{r},t) = 0$$

Electrodynamic boundary conditions

$$H_e \cos\theta_e = H\cos\theta\,; \qquad H_e \sin\theta_e = [H + M_z]\sin\theta$$

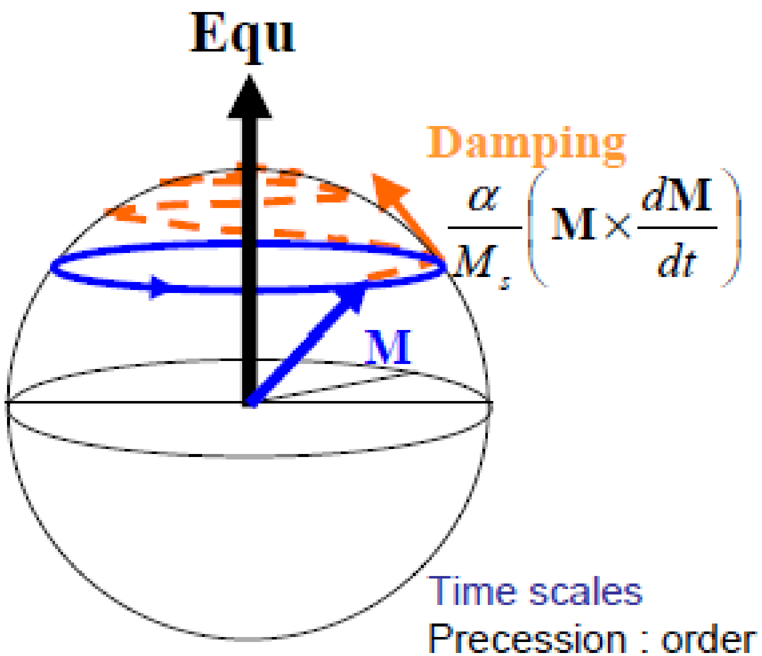


These conditions do NOT fix value of magnetization at the boundary

Micromagnetism: Magnetization motion

Landau-Lifshitz-Gilbert Equation (LLG)

$$\frac{d\mathbf{M}}{dt} = \underbrace{\boxed{-\gamma(\mathbf{M}\times\mathbf{H}_{eff})}}_{\text{Precession}} + \underbrace{\boxed{\frac{\alpha}{M_s}\left(\mathbf{M}\times\frac{d\mathbf{M}}{dt}\right)}}_{\text{Damping}}$$



Time scales
Precession : order or below ns
Damping : few ns

1) Norm of **M** Conserved

$$\mathbf{M}\frac{d\mathbf{M}}{dt} = 0$$

2) Energy **NOT** Conserved

$$\frac{dE}{dt} = -\frac{\gamma\alpha}{M_s}\left(\frac{d\mathbf{M}}{dt}\right)^2 < 0$$

→ Damping decreases the energy

3) Static States $\mathbf{M}_o$

$$\frac{d\mathbf{M}}{dt} = 0 \Rightarrow \mathbf{M}_o \Leftrightarrow (\theta_o, \varphi_o)$$

Same as for conservative dynamics
Since dM/dt=0

LLG equation is nonlinear integro-differential eq.

Application(s) of numerical micromagnetics

Modern computer technology

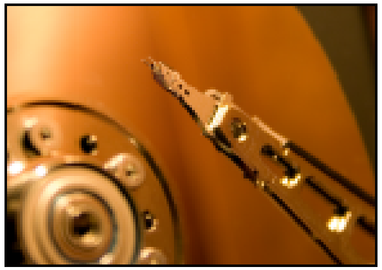
High-density information storage

High-speed read-write processes

Optimization of the **hard disk** magnetic properties

Optimization of the magnetization **switching dynamics**

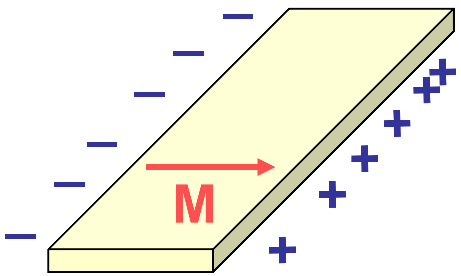
Extensive micromagnetic simulations **mandatory**



Without numerical micromagnetics → **No modern computer facilities**

D. Berkov

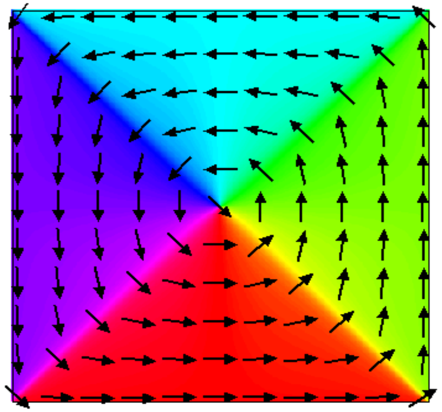
Introduction: patterned magnetic films



How are spin dynamics (eigenfrequencies and eigenmode profiles) influenced by confinement?

1. What are the normal spin-excitation modes of an inhomogeneous magnetic system?

2. How is their “character” determined by geometrical sizes and shape?



- Transverse magnetized stripes - inhomogeneous internal field

- Domain structures and magnetic **vortices** - inhomogeneous magnetization

1. Dimension of system (D)- magnetostatic modes for $\lambda \sim D$
.
2. Domain wall thickness $\delta = \pi\sqrt{A/K}$ and exchange length $L_{ex} = \frac{\sqrt{2A}}{M_S}$

Experiment: time/space or frequency domain/momentum space

Analytical calculations + micromagnetic simulations

Length scales: 10 nm to 10 μm; Time scales: 50 ps to 10 ns

Summary

1) Mesoscopic magnetic structures provide now a wide testing area for concepts of nanomagnetism and prospective applications

2) Magnetic vortex in nanodot having two stable discrete states of polarization and chirality is a promising candidate for high density magnetic recording (non-volatile data storage devices)

3) Understanding the stability and dynamic behavior of magnetic patterned structures is on the forefront of modern science and technology